



STO MEETING PROCEEDINGS

MP-MSG-943

Towards the Next Generation Synthetic Battlespace

(Vers la prochaine génération de représentation
synthétique de l'espace de combat)

STO Modelling & Simulation Group (NMSG) Symposium held on 24-25
October 2019 in Vienna, Austria.



Published October 2019

The NATO Science and Technology Organization

Science & Technology (S&T) in the NATO context is defined as the selective and rigorous generation and application of state-of-the-art, validated knowledge for defence and security purposes. S&T activities embrace scientific research, technology development, transition, application and field-testing, experimentation and a range of related scientific activities that include systems engineering, operational research and analysis, synthesis, integration and validation of knowledge derived through the scientific method.

In NATO, S&T is addressed using different business models, namely a collaborative business model where NATO provides a forum where NATO Nations and partner Nations elect to use their national resources to define, conduct and promote cooperative research and information exchange, and secondly an in-house delivery business model where S&T activities are conducted in a NATO dedicated executive body, having its own personnel, capabilities and infrastructure.

The mission of the NATO Science & Technology Organization (STO) is to help position the Nations' and NATO's S&T investments as a strategic enabler of the knowledge and technology advantage for the defence and security posture of NATO Nations and partner Nations, by conducting and promoting S&T activities that augment and leverage the capabilities and programmes of the Alliance, of the NATO Nations and the partner Nations, in support of NATO's objectives, and contributing to NATO's ability to enable and influence security and defence related capability development and threat mitigation in NATO Nations and partner Nations, in accordance with NATO policies.

The total spectrum of this collaborative effort is addressed by six Technical Panels who manage a wide range of scientific research activities, a Group specialising in modelling and simulation, plus a Committee dedicated to supporting the information management needs of the organization.

- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS System Analysis and Studies Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

These Panels and Group are the power-house of the collaborative model and are made up of national representatives as well as recognised world-class scientists, engineers and information specialists. In addition to providing critical technical oversight, they also provide a communication link to military users and other NATO bodies.

The scientific and technological work is carried out by Technical Teams, created under one or more of these eight bodies, for specific research activities which have a defined duration. These research activities can take a variety of forms, including Task Groups, Workshops, Symposia, Specialists' Meetings, Lecture Series and Technical Courses.

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Towards the Next Generation Synthetic Battlespace

(STO-MP-MSG-171)

Executive Summary

The NATO Modelling and Simulation Group (NMSG) Conference (MSG-171), “Towards the Next Generation Synthetic Battlespace,” was conducted in Vienna, Austria on 24 & 25 October 2019. All sessions of the Conference were unclassified. The Conference audience included participants from NATO countries, Partners-for-Peace (NP) nations, and invited nations. At the Conference, 18 papers were presented. A national presentation and an invited presentation were given at the beginning of the first day. Additionally, a panel session and two poster sessions were presented on the first day. The second day opened with the NMSG Young Scientist Award Presentation. Conference contributions were presented throughout in seven topic sessions. This Technical Evaluation Report summarizes the core ideas and results presented in this conference. This report also provides an overview of discussions conducted during the conference and concludes with a summary and recommendations section.

The theme for MSG-171 was the next generation synthetic battlespace. This theme reflects the need for M&S systems to modernize in order to better represent the complex and contested future operating environment and its effects. This scope covers a large spectrum of topics such as cyber, influence/information operations, space, autonomous systems, C4ISR & military-civil decision-making support, human behaviour, climate conditions, and simulation architectures.

Topics included future military and civilian challenges in the space, modelling the complexity of human behaviour, the challenging modelling domains of space and cyber, advances in the representation of chemical, biological, radiological and nuclear (CBRN) effects, applications of augmented reality / virtual reality (AR/VR), evolving architectures, and simulation of non-traditional warfare environments such as urban and subterranean terrain.

Summary recommendations include taking a more holistic approach to identifying future NMSG activities which is in keeping with the increasing complexity of integrated M&S and representation of systems of systems. Additionally, other presentation formats may increase knowledge acquisition benefits to participants, e.g. explicitly requesting shareable lessons learned and metrics in paper and panel sessions focused on applying new technologies. External to the symposium itself, value may be provided to participants through a virtual mechanism, e.g. a wiki or knowledge base, for sharing results of ongoing work. The summary recommendations also include suggestions for future topics.

Vers la prochaine génération de représentation synthétique de l'espace de combat

(STO-MP-MSG-171)

Synthèse

La conférence du Groupe OTAN sur la modélisation et la simulation (NMSG) (MSG-171) intitulé « Vers la nouvelle génération d'espaces de bataille synthétiques » s'est déroulée à Vienne, en Autriche, les 24 et 25 octobre 2019. Toutes les sessions de la conférence étaient sans classification. Le public de la conférence incluait des ressortissants des pays de l'OTAN, des pays du Partenariat pour la paix (PPP) et des pays invités. Dix-huit articles ont été présentés pendant la conférence. Un exposé national et l'exposé d'un invité ont été présentés au début de la première journée. En outre, une réunion de spécialistes et deux présentations visuelles ont eu lieu le premier jour. La deuxième journée s'est ouverte sur la présentation du prix du jeune scientifique du NMSG. Des contributions sous forme de conférence ont été apportées lors de sept sessions thématiques. Le présent rapport d'évaluation technique résume les idées centrales et les résultats exposés pendant cette conférence. Ce rapport donne également une vue d'ensemble des discussions menées pendant la conférence et se termine par un résumé et des recommandations.

Le thème du MSG-171 était la nouvelle génération d'espaces de bataille synthétiques. Ce thème reflète le fait que les systèmes de M&S doivent se moderniser afin de mieux représenter le futur environnement opérationnel complexe et contesté et les effets de celui-ci. Ce champ couvre un large spectre de sujets tels que la cyberdimension, les opérations d'influence/information, l'espace, les systèmes autonomes, le C4ISR et l'aide à la décision militaire et civile, le comportement humain, les conditions climatiques et les architectures de simulation.

Les sujets traités ont été les suivants : les défis militaires et civils dans l'espace, la modélisation de la complexité du comportement humain, les domaines difficiles à modéliser que sont l'espace et la cyberdimension, les progrès de représentation des effets nucléaires, radiologiques, biologiques et chimiques (NRBC), les applications de réalité augmentée/virtuelle (RA/RV), l'évolution des architectures et la simulation d'environnements de guerre non traditionnels, tels que les environnements urbain et souterrain.

En résumé, les recommandations sont notamment d'adopter une approche plus globale de l'identification des futures activités du NMSG, qui soit conforme à la complexité croissante de la M&S intégrée et de la représentation des systèmes de systèmes. De plus, d'autres formats de présentation peuvent accroître les bénéfices en termes d'acquisition des connaissances par les participants, par exemple, le fait de demander explicitement une version papier des enseignements retenus et des indicateurs de mesure et le fait de focaliser certaines réunions de spécialistes sur l'application des nouvelles technologies. À l'extérieur du colloque en soi, les participants pourraient tirer profit d'un mécanisme virtuel, par exemple un wiki ou une base de connaissances, pour partager les résultats des travaux en cours. Le résumé des recommandations inclut également des suggestions concernant les futurs sujets à étudier.

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Technical Evaluation Report

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EXECUTIVE SUMMARY

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1.0 INTRODUCTION

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This Technical Evaluation Report contains a synopsis of the plenary and paper presentations. Also included are significant technical and thematic aspects of the conference, concluding with recommendations for

consideration by the organizers. While this Technical Evaluation Report serves as a record of the conference's activities, the best source of the information presented are the original papers and the related presentation materials.

2.0 DAY 1 (THURSDAY, 24 OCTOBER 2019)

2.1 National Presentation: Future Challenges for Austrian Armed Forces; Major-General Mag. Bruno HOFBAUER (Director Strategic Planning Directorate, Austria)

Major-General Mag. HOFBAUER began with an admonition against business as usual. Decades of peace have led to wishful thinking that military confrontation will not return. Contemporary war will happen in the "grey" zone, e.g. Ukraine and the South China Sea. Additionally, non-state actors are becoming increasingly sophisticated. He highlighted his areas of key concern:

- Hybrid warfare on the political, diplomatic, and economic levels including information operations, troop movements, cyber warfare, and disinformation. Artificial intelligence and the Internet of Things will accelerate hybrid warfare.
- Urbanization, both within and outside cities, will challenge us, e.g. high rises and subterranean dwellings. So, Realistic urban and subterranean training must become normal, not the exception. Sixty percent of the world's population currently lives in urban environments. Cities that grow the fastest will present the greatest challenge as non-governmental forces will fill gaps left by overextended governments. And those cities will be too large to cordon and control. The dense population will provide an abundance of human shields, and media relations (permanent media scrutiny) will be tools of non-state actors
- We must always be advancing our modern warfighting capabilities because the technological advantage of the military will be short-lived, e.g. drones. And we're already behind on communications equipment. We need to advance our use of autonomy and artificial intelligence (AI) while balancing ethical constraints our enemies don't have, e.g. support for fire control.
- Digitization will be the key driver for the next century, so we need more cyber warriors.
- Major-General Mag. HOFBAUER concluded by identifying areas where M&S can help with training:
 - Faster testing of tactics, techniques, and procedures (TTPs) and force structures
 - Expanding the size of the training space
 - Efficacy of integration of new technologies, e.g. autonomy
 - Threat representation
 - Urban environments

2.2 Invited Presentation: Security Challenges for Austrian Armed Forces; Dr. Ralph Hammer (Federal Ministry for Transport, Innovation and Technology, Austria)

Dr. Hammer's presentation focused on KIRAS, a critical infrastructure protection programme of the Austrian Federal Ministry for Transport, Innovation and Technology. This briefing was a valuable counterpoint to the preceding briefing because KIRAS has a civil focus, although it can be dual use. KIRAS selection maximized societal consent for projects, i.e. solutions that are socially acceptable. M&S-related projects include:

- Simulation of threat and damage potential of explosive devices at the urban level

- Evacuation scenarios
- Cyber security incidents tailored to Austrian companies
- Optimal first responder deployment during mass events
- Acoustic impact of stun grenades
- Police training for societal hot spots
- Interdependent critical infrastructure
- Risk analysis of energy grids
- Anomaly detection in industrial control / SCADA
- Preparedness in energy (blackout) and crisis situations

KIRAS is considering some “out of the box” new simulation proposals including an unsolvable situation similar to the “Kobayashi Maru” test, an exercise with no electricity or communications, and an exercise with a human or obstacle in the loop. The last of these is intended to get at the question of how effective / realistic the inclusion of a human decision-maker can be in the age of full, automatic engagement.

2.3 Session 1 – Modelling the Next Generation Synthetic Battlespace – Human Actors

Session 1 Chair – COL Wolfgang KRALICEK (MoD, Austria)

2.3.1 Paper #1 – Using Behaviour Trees to Model Battle Drills for Computer-Generated Forces; Per-Idar Evensen, Håvard Stien, Dan Helge Bentsen

Paper Abstract: *Modelling realistic human behaviour, including decision-making and creativity, is the hardest and most complex challenge in combat simulation. Behaviour trees (BTs) is a relatively new and increasingly popular approach for developing behaviour models for artificial intelligence (AI) and intelligent agents. The approach has become especially popular for creating behaviour models for non-player characters (NPCs) in computer games, robots, and autonomous vehicles.*

BTs are represented as directed trees with a hierarchy of control flow nodes and task nodes that control the behaviour of an agent. What makes BTs so powerful is their composability and modularity. Task nodes and control flow nodes are composed into subtrees which represent more complex actions, and these actions can be composed into higher level behaviours.

In this paper we will give an introduction to BTs based on available literature and discuss the possibilities and limitations of employing this modelling technique for creating behaviour models for computer-generated forces (CGF) in combat simulations. Furthermore, we will give a concrete example of how to create a BT from a textual description of a battle drill, and provide tips and tricks on how to create BTs in general. Finally, we will summarize our experiences from working with BTs.

Discussion: This paper focused on the application of BTs to increasing combat effectiveness in land force operations. BTs are directed, rooted trees that represent all the possible courses of action an agent can take. The author asserted that BTs are powerful because of composability and modularity. It is not currently feasible to use AI to build very complex BTs. Capturing behaviour of real units in exercises might be a farther future experiment to generate models more easily. The following questions are derived from the paper, but there was insufficient time to answer them during the presentation:

1. *We found that hands-on experimentation with different control flow patterns was very useful to better understand how BTs work, and how to create good BTs. What specific lessons were learned through experimentation with different control flow patterns?*

2. *It is good practice, at the start of a subtree, to always make sure things are configured correctly before continuing and not assume anything was correctly configured before.* This sounds like you want to check that the environment hasn't changed. But wouldn't the process of executing the BT from the root node check the status of the environment? And wouldn't control flow nodes with memory exacerbate this problem because they would retain "stale" state?
3. *The behaviour models also need to be validated, and this will typically be done by face validation by military SMEs and officers from the Norwegian Army.* Have you considered more rigorous validation methods?
4. *To make this possible we need to ensure that the models also exist as conceptual models that can be implemented in other simulation systems.* Discuss BTs as a form of conceptual model. How do they compare to other forms, e.g. sequence diagrams?

Recommendation: See summary recommendations 2 and 3. Answers to the above questions could be provided virtually.

2.3.2 Paper #2 – Computer Modelling of Human Populations in Support of Military and Civil Command and Control (C2) Exercises; David Robson

Paper Abstract: *This paper discusses the design of a computer modelling framework for a UK military training and education requirement, lessons learned during its construction and implications for representing the complex and contested future operating environment.*

The "Influence and Infrastructure Combat Model" (IICM) is a computer simulation that models the flow of information and resources through a Human Terrain and the supporting critical national infrastructure networks (CNI). This project began as a study on methods of modelling the effects of Cyber activities on a local population and was extended to include wider military actions including Hybrid, Military Operations in Urban Areas (MOUT) and Informational Manoeuvre activities.

IICM treats the population as an unstable equilibrium destabilised by external actors. Drawing upon group dynamics theory and epidemiological compartment modelling techniques, information is modelled as mimetic packets which are passed between software agents representing population groups, changing the level of support for different factions. These act as a quantifiable 'target' for influence operations within an exercise.

Drawing on our experience in military exercising, IICM is designed to operate as an independent model or federated with a kinetic warfare simulation. It presents effects as seen by the military decision maker, rather than the low-level analyst or system operator.

Discussion: The speaker provided an overview of shortcomings of current kinetic simulations, e.g. very low-resolution representations of urban environments. There is a need to represent cyber and civil populations and deal with resistance to the impacts of those on traditional kinetic training. They're looking for indicative rather than predictive outputs for non-kinetic representations. Contemporary manual wargames are making faster progress on the mathematics in this domain than the military. Getting social interaction results back into kinetic simulations is a challenge because the kinetic simulations aren't designed to take those results as inputs. The bulk of the presentation focused on the underlying models of population behaviour.

The paper lists the following as elements of the simulation: Cyber and CNI disruption change electronic communications; a "Capacity based Comms model" models electronic information flow; information flows through a population; an "Agent based Social Interaction model" models the transmission of influence between people. The introduction of two nascent modelling domains, human and autonomous systems

behaviour (HASB) modelling, and responses to electronic communication disruptions might confound understanding of underlying impacts and make it hard to validate the federated simulation. The speaker concurs that doing so could be almost impossible, particularly because of second and third order effects. Messages representing social interactions are handled by a handful of SMEs because the task is so challenging, e.g. breaking down an input like a newspaper article and figuring numeric changes in sentiment.

Recommendation: HASB is a broad, deep, significantly-challenging modelling domain that needs more persistent attention. See summary recommendations 4.a and 4.b.

2.3.3 Poster Session

Data Farming

This poster provided an overview of the architecture to realize the recommendations of MSG-155 for data farming core services. These services are intended to enable a simulation-based methodology to support defence planning, operations planning, warfare development, and concept development and experimentation via multiple simulations runs. This poster was unstaffed, so the following questions were not answered:

- What techniques and tools are being used?
- What data from each of the use cases will be examined?
- What types of outcomes might be expected?

C2SIM

C2SIM integrates C2 systems with simulations via interceding software, eliminating the need to modify C2 systems which is infeasible. Its implementation as a service realizes NATO's M&S as a service (MSaaS) vision. The C2SIM project also participates actively in standards including the Simulation Interoperability Standards Organization's (SISO's) C2SIM and Cyber Data Exchange Model (DEM).

Navantia's Digital Twin Implementation Perspective in Military Naval Platform Life Cycle; Juan Ignacio Silvera, Juan Luis Muñoz, José María Luquero, Angelina Cajade, Manuel Bustelo

This paper describes Navantia's proprietary Digital Twin architecture and integrated NAVANTIS training suite. The approach to developing this architecture is intended to meet current best practices including developing a conceptual architecture that is modular, scalable, data-oriented, and data-driven via agile methods. These observations are based on reading the paper because no poster was provided, and the poster briefer was not familiar with the work.

Recommendation: The poster sessions would have been more effective with printed posters at each station and briefers present to answer questions.

2.4 Session 2 – Modelling the Next Generation Synthetic Battlespace – Systems and Sensors

Session 2 Chair – Wim HUIKAMP (TNO, The Netherlands)

2.4.1 Paper #3 - Simulating the Future Operating Environment for Training and Education; Matthew Smith, Neil Smith

Paper Abstract: *Military operations are performed in an increasingly complex world where the behaviour of force elements is affected by the state of the natural environment, political effects and social effects, in addition to physical (kinetic) warfare effects.*

Modelling and Simulation (M&S) systems have a limited representation of these aspects, and mainly provide static representations of the natural environment and physical warfare effects. The effects of electronic and information warfare such as offensive and defensive cyber and the use of social media as an influence tool are of increasing importance to military users. Current synthetic based training systems employ a component known as Computer Generated Forces (CGFs) to represent the majority of human and systems behaviour as an integral element of the simulation and/or Synthetic Environment (SE) used to deliver the training. However, no single CGF adequately represents the breadth of system, human, organisational and social behaviours that occur in operational environments, and often more than one CGF needs to be employed which were not designed to be interoperable which impacts the ability to provide consistent representation of effects across dissimilar simulation systems. This is a capability gap identified by previous research carried out by the UK Defence Science and Technology Laboratory (Dstl) in partnership with supplier organisations. Related to this issue, “Simulating Future Battlespace Complexity” is one of five UK Defence Innovation Priorities published by the UK MOD.

This paper describes research conducted by the UK Defence Science and Technology Laboratory (Dstl) into the representation of Future Operational Environments (FOE) in Simulation (FOESim). This is aimed at investigating methods and technologies relevant to representing the increasing complexities of operational environments in simulation in a more coherent and effective manner. The scope of this research includes,

- assessing opportunities for M&S to provide more efficient and effective training in Future Operating Environments (FOE);*
- new approaches for the composition of more coherent and improved representation of human and systems behaviour across simulation systems;*
- the representation of warfare effects on current and emerging operating domains such as space and cyber, including non-physical force behaviours such as electronic and information warfare effects;*
- consistent representation of dynamic natural effects such as weather and terrain on operational environments;*

Discussion: The presenters provided an overview of several existing modelling challenges, e.g. composability, cyber, human behaviour, autonomous system behaviour, social media. Interaction with various MSGs is key to achieving their research aims:

- Modelling and Simulation as a Service (MSaaS) (MSG-136, -164)
- Environmental effects (MSG-156, -163)
- Simulation open standards (MSG-145)
- Representation of human and autonomous behaviours (MSG-127)
- Representation of non-physical effects (MSG-151, -170, -181)
- Representation of autonomous systems (MSG-154, -183)

This overview led to a discussion about preventing various NMSG activities from becoming stove-pipes. A top level down, more structured approach was discussed. With respect to MSG-127 and the previous discussion of HASB modelling challenges, it was observed that a lack of available behavioural data sets to serve as a basis for building or validating HASB models remains a challenge. The briefer reported that Dstl is just about to let contracts to collect such data, but there are ethical and legal issues with collecting and using this data.

Recommendation: Research overview briefings such as this one are most valuable to attendees if they can apply the results to their own efforts. See summary recommendation 2. This project and the one described in

paper #4 should coordinate as they both face the challenge of validating HASB models. See summary recommendation See summary recommendation **Error! Reference source not found.**

2.4.2 Paper #4 - The Representation of Information Warfare Effects in the Synthetic Battlespace; Keith Ford, Deryck Arnold

Paper Abstract: *The current generation of Simulations and Synthetic Environments (SEs) focus on physical warfare effects and do not adequately represent the wider spectrum of activities in the operational environment. In order to provide a more realistic environment, the next generation synthetic battlespace must include a better representation of other aspects of operations including information warfare, infrastructure, logistics, human interactions and the general populace.*

Thales has led a project on behalf of the Defence Science and Technology Laboratory (Dstl) in the UK to research the provision of Information Warfare effects in the synthetic battlespace. This includes the ability to deny, degrade, corrupt or destroy the enemy's sources of information whilst preserving its own. The future synthetic battlespace must also get synthetic entities to change their behaviour as a result of the information they receive through sources such as web sites, social media, television and radio.

To promote the reuse of Modelling and Simulation (M&S) across the defence community, the UK MOD has a desire to move away from monolithic simulations to more component architectures when representing the synthetic battlespace. In keeping with this approach, Thales has developed a 5 layer communications model in which the information can be manipulated at different stages of the communications chain.

Discussion: The speaker led with a humorous simulated information warfare attack followed by an overview of information warfare effects. He related this to his 3-axis battlespace model: environment (LVC), cognitive, and 5-layer communications model. With respect to V&V of such simulations, the briefer acknowledged that he had no methodology for cyber simulations, and that V&V for behaviour models is particularly challenging.

Recommendation: Given that they project using SISO's C2SIM in the future, the project should get engaged with the SISO Cyber M&S effort, especially the Cyber DEM. This project and the one described in paper #3 should coordinate as they both face the challenge of validating HASB models.

2.4.3 Paper #5 - Introduction of Unmanned Airborne Combat Systems into Future Threat Scenarios: Opportunities and Challenges; Marco Weiß, Johannes Haindl, Florian Gräßel

Paper Abstract: *In future air combat, the integration of unmanned cooperative systems will be a potentially huge force multiplier. Key factors for its success will be teaming intelligence, coordinated mission planning and cross-platform mission management. Therefore, the task of conceptualizing the next generation airborne weapon system requires a holistic system-of-systems approach that considers the different air vehicles itself, their avionics mission systems and the overall concept of operation against future threats. For early validation of possible solution concepts and assessment of their operational performance, a dynamic multi-agent combat simulation has been developed over the last years within Airbus Defence & Space Future Projects. In addition to its faster-than-real-time engineering functionality, the simulation allows real-time human-in-the-loop experiments to foster collaboration between engineers, operators and customers. This paper presents our approach to dynamic mission simulation and insights from the application of our tool during the Future Combat Air System (FCAS) studies, during which it became clear what will be a key challenge for future applications: Implementing a robust high-level planning algorithm that generates ad-hoc mission plans for complex air operations while considering reactive low-level agent behaviour, human operators and online user input.*

Discussion: The abstract indicates this paper focuses on significant advances in simulation to support evaluation of unmanned cooperative systems, but the bulk of the paper is about a federated, constructive

simulation of the type that has been in use for decades. The presenter provided an overview and history of the Future Combat Air System (FCAS) followed by well-known modelling and simulation issues. Their approach to dealing with disruptive technologies appearing in the future is to use a stochastic, Monte Carlo tool to investigate parameter sensitivity. But the brief acknowledged that they can only simulate what they know. They are currently engaged in concept design, only representing current air warfare tactics, not experimenting with new tactic representation.

Recommendation: The authors should get engaged with the SISO Cyber DEM effort. Also see summary recommendation 4.b.

2.5 Panel Session – The NMSG and The Next Generation Synthetic Battlefield

Panel Chair – Dr. Robert SIEGFRIED, Vice-Chair NMSG (Aditerna GmbH, DEU)

Panel Members:

- Agatino MURSIA, Chairman NMSG (Leonardo Company, Italy)
- Dr. Andreas TOLK (The MITRE Corporation, USA)
- Dr. Keith FORD (Thales UK, United Kingdom)
- Dr. J. Mark PULLEN (George Mason University, USA)
- Lesley JACOBS (TNO Defence Research, The Netherlands)

Discussion: Dr. Siegfried opened the panel by putting the following questions to the panel members:

1. What are the real drivers / challenges for future work?
2. What is the role of the NMSG in this future work?

Panelist	Drivers	NMSG's Role
Agatino Mursia	• Combination of technology and political issues, e.g. ○ AI, “Whoever rules AI will rule the world.” – <i>Putin</i> ○ The potential power of quantum computing, especially with respect to AI	• Attract early career engineers and scientists and pair them up with operational warfighters • Champion migration of technologies, e.g. MSaaS, from concept to implementation
Andreas Tolk	• Operational agility • Autonomous systems	• Education • Contribute to technical solution
Keith Ford	• Outside phase 3, dominate, of warfare • Non-lethal effects, e.g. dazzle lasers, stun grenades, acoustic hailer, tasers • Information warfare	• Weather (including terrain impacts) • Human behaviour • Information warfare • Infrastructure logistics, e.g. traffic • Populace
Mark Pullen	• Geopolitics • Breadth of information, threats, and countermeasures • Cyber	• Support alliance cohesion systems and technologies • Spot and encourage scalable innovation

Lesley Jacobs	Multi-domain battlespace: information, physical, human	- Integrated analysis of M&S, Data science, operational analysis - Persistent synthetic battlespace capabilities

Discussion: After answering the initial questions, the subsequent discussion included the following observations. Information warfare simulation is challenging because it gets highly classified almost immediately. As a community, we don't know about social sciences simulations while we need to understand both the cyber and HASB aspects. We still don't know how to model influence. Progress is hindered by a lack of trust among the NATO nations with respect to sharing existing data "owned" by the nations. Even so, SMEs agree that, in most cases, the data available is insufficient to validate simulations.

How can simulation support the requirement to reduce military fuel use to meet the 2030 requirement in the Paris Accords? Higher resolution representations of logistics, i.e. fuel, are required. "The Uninhabitable Planet Earth" identifies 12 individual effects, but doesn't analyse the interacting effects which could be done via simulation.

Recommendation: The panel itself provided recommendations for paths forward. STO should create policies to support data sharing including output data and validated system representations. A new task group on information warfare should be started; it should result in a persistent international simulation capability with data storage and sharing.

2.6 Session 3 – M&S in Support of Operations

Session 3 Chair – Prof. Andrzej NAJGEBAUER (Military University of Technology (MUT), Poland)

2.6.1 Paper #6 - Optimizing Flight Paths Through Anti-Aircraft Gun Fire with Machine Learning; Esben Lund, Bernt Almklov, Runhild A. Klausen

Paper Abstract: We present a methodology intended to optimize the flight path through a flight corridor occupied by enemy anti-aircraft guns. This is relevant for all kinds of aircraft, missiles, and drones moving through air space that is fully or partially controlled by such guns. To this end we use Q-learning - a type of reinforcement (machine) learning - which tries to find the optimal strategy to avoiding the anti-aircraft guns through repeated semi-random flight path trials. Q-learning can produce an optimal flight path through the enemy fire without modeling the anti-aircraft guns directly. An adversary response is still needed, but this can come from a black box simulation, user input, real data, or any other source. Here, we use an in-house tool for generating the anti-aircraft fire. This tool simulates a close-in weapons system (CIWS) guided by a fire control radar and Kalman flight path prediction filters. Q-learning can also be supplemented with neural networks - so-called deep Q-learning (DQN) - to handle even more complex problems. In this work, we present results for a subsonic flight corridor pass of one anti-aircraft gun position using classic Q-learning (no neural networks).

Discussion: The presenter described the specifics of the operational environment represented, i.e. anti-aircraft fire. He proceeded with an overview of machine learning approaches including unsupervised learning, supervised learning, and reinforcement learning. From there he walked through the calculations of Q-values for the optimized flight path problem and showed results for large numbers of episodes. It might be possible to use this method to represent the anti-aircraft gun. There is a plan for incorporating this into a larger simulation involving UAVs. The following questions are derived from the paper, but there was insufficient time to answer them during the presentation:

1. What other applications might this have?

2. Might this learn the wrong lesson by not representing all aspects, e.g. radar? Should it not look at more parameters?

Recommendation: See summary recommendations 2 and 3. Answers to the above questions could be provided virtually.

2.6.2 Paper #7 - Intelligence Tools for Environmental Threats: Integrated Technologies for Chemical Hazards; Jodi L. Ryder, Victor F. Medina, Manoj K. Shukla, Josh J. Lemonte, Christa M. Woodley

Paper Abstract: *Accounting for environmental hazards in mission planning requires the most up-to-date observations and forecasting of the dynamic battlefield environment. In addition, some hazards, such as the exposure to toxic industrial chemicals and materials (TIC/Ms) in complex urban environments, cannot be predicted in time and space without significant a priori knowledge of TIC/Ms presence in the battlefield, potential release scenarios, and the dynamic ongoing natural environmental processes that result in hazardous soil, water, and air exposures. Teams at the US Army Engineer Research and Development Center (ERDC) are engaged in the development of tools to improve the timeliness and reduce the uncertainty of TIC/Ms risk identification through the integration of spatial and database tools including probable TIC/M locations and quantities, toxicological hazards, fate and transport properties, and soil properties. Furthermore, ongoing efforts to expand the reach of operational hydro-meteorological prediction allow these tools to be applied in rapid fate and transport modelling with greater certainty over a larger swath of the globe than is presently possible. The end result will enable more accurate and dynamic understanding of the chemical hazard potentials that can be encountered during battlefield operations, allowing for better informed routing and equipment selection.*

Discussion: This work is to be commended for the effort to improve multiple dimensions of the representation in this challenging domain by integrating existing, authoritative, disparate sources and tools including US Environmental Protection Agency (EPA) Toxic Release Inventory (TRI), Joint Warning and Reporting Network (JWARN), Incident Command for Drinking Water Protection (ICWater), Specialized Hazard Assessment Response Capability (SHARC), and Hazard Prediction and Assessment Capability (HPAC). Potential future applications could include integrating offline best- and worst-case scenarios as input to more complex constructive simulation environments for the purpose of improving mission effectiveness analysis.

Recommendation: When the research and engineering activities are complete, the results of this effort could be very interesting. See summary recommendations 2 and 3.

2.7 Session 4 – Synthetic Environment

Session 4 Chair – Niels KRARUP-HANSEN (DALO, Denmark)

2.7.1 Paper #8 - Modelling & Simulation for Underground Operations; Major Christian RESCH

Paper Abstract: *Due to the increasing volume of traffic and the resulting efforts of the society to reduce traffic in urban areas and settlements, to build bypasses or due to the topography to move this partially underground. Resulting in an increasing number of complex traffic and safety concepts, which include underground infrastructure. From a fire safety perspective, hazards are manageable and risks are largely calculable. The scenario of a dangerous goods accident in a road tunnels or the release of chemical agents into underground facilities is treated very sparingly (if at all), neither are military concepts for underground operation. However, the attack with Sarin on Tokyo's subway in 1995 shows that underground facilities in particular have a particular vulnerability here.*

Discussion: The presenter began with a description of potential underground vulnerabilities in Vienna, illustrating the types of hybrid threats in his paper: railways, metro, tunnels, canals, parking, shopping malls, and event halls. Most recent R&D has focused on mining, less so on underground infrastructure representation for military or first responder applications. He highlighted specific challenges: geology and construction; water and chemicals; limitations in effects of actions; operations under extreme conditions - movement, TTPs, darkness, obstacles, logistics, communication. The MoD is building 3D models of read underground structures using LIDAR while universities are building models of materials. Applications of this work include: hazard, risk and vulnerability assessment; intelligence preparation of the environment (IPE); protection technologies; TTPs; infrastructure protection / enhancement; emergency planning; and VR/AR training. Visualization is challenging because usual 3D projection systems don't work well with tunnels. The project is working more with assessing team effectiveness within enclosed environments, especially in training first responders.

Recommendation: A demonstration or video of the resulting training capability could be very informative. See summary recommendation 3.

2.7.2 Paper #9 - Representation of Dynamic Synthetic Environments in Distributed Simulation; Arno Gerretsen, Neil Smith, Ruben Smelik, Ralf Stueber

Paper Abstract: *Current practices, standards and technologies are aimed at achieving correlated static synthetic representations of Defence operational environments across distributed simulation systems. However, real world operational environments are dynamic in nature. Weather varies with time and place, and the terrain is affected by both natural effects (e.g. heavy rainfall, snow, flooding) as well as the effects of force behavior, such as munitions damage to buildings and infrastructure. Where multiple simulation systems are federated, both the static and dynamic representation of the operational environment needs to be consistent.*

This paper describes work being carried out by the MSG-156 Task Group (TG) to investigate simulation architectures, processes and standards aimed at achieving improved and consistent representations of dynamic environments across simulation systems. This includes the representation of weather data in simulation, processes to dynamically modify the terrain and protocols for simulation systems to retrieve the current state of the simulated operational environment. Modelling and Simulation as a Service (MSaaS) is assessed as being a key enabler required to achieve this.

This paper describes a set of Use Cases and the Conceptual Models that has been derived from these Use Cases. A proposed architecture for achieving a consistent dynamic synthetic environment is also included, together with a description of planned experiments to evaluate the proposed solution.

Discussion: The speaker began by identifying the MSG-156 focus areas: dynamic terrain and variable weather. He proceeded by describing the program of work and reporting MSG-156's progress against the program. Latency has been identified as a performance requirement, but the actual metrics haven't been worked out. At this point, the project is mostly focusing on concepts and worrying less about performance requirements because technology will continue to improve. MSG-164 may be providing draft interface specifications for MSaaS next year. Although they don't yet have any preliminary concepts of needed standards, they would consider pursuing those through SISO in the future. They are currently looking at SEDRIS as a source of representations. Although all the use cases are military, this technology also has civilian application.

Recommendation: See summary recommendation 3.

3.0 DAY 2 (FRIDAY, 25 OCTOBER 2019)

3.1 NMSG Young Scientist Award Presentation - Reliability Requirements for Augmented Reality in Visual Search Tasks; Samuel S. Monfort, John J. Graybeal

Paper Abstract: *In military operations, quick and accurate target detection and identification is critical for mission success. Augmented reality (AR) technologies can aid target detection and identification by layering digital imagery atop a Soldier's field of view to increase situational awareness. These systems are rarely perfect, however, and in some cases unreliable AR may actually interfere with performance. This investigation focused on the capacity for unreliable AR to impair performance. We showed participants a series of simulated two-dimensional scenes where highly-visible AR cues were superimposed over tanks placed randomly in a grassland environment. The reliability of these cues varied (from 25% to 100%) throughout the experimental session, as some valid targets were erroneously un-marked (false negatives) while some invalid targets were erroneously marked (false positives). Participants were asked to search for the vehicles while being assisted by the AR; search accuracy and response time were analyzed, and participants provided feedback regarding their mental workload and trust in the AR. We found the expected negative relationship between unreliability and performance, but also found that AR false positives were more damaging to performance than AR false negatives. Unreliable AR also hurt performance more when marking vehicles at greater distances. Further, although error type and target distance had powerful effects on participant performance, they had less of an impact on subjective trust and workload, suggesting that Soldiers using AR might not be consciously aware of how their own performance changes as a function of AR properties. In summary, unreliable AR hurt performance differently depending on the type of errors produced by the system, and impaired some aspects of performance but not others. These results carry important implications for how AR is designed to improve performance on the battlefield.*

Discussion: Testing engineers' hypotheses about the value of cool new tech. How accurate does AR have to be to improve human performance? Contribute to general AR usage guidelines; adapt our existing simulation capabilities to be able to answer sensor- and task-specific questions. False alarms are more damaging than misses. Distance magnifies the undesirable effects of unreliable AR. Although false alarms are more damaging, misses cause more resource drain because those participants increase effort to compensate. Overwhelmingly people with stimuli causes them to withdraw. Future AR systems may allow users to adjust detection thresholds, i.e sensitivity. There is a tangible cost to automating a task that cannot be automated well, e.g. target detection at distance. This study has led to others at NVEDS:

- Visual search in a. high clutter environment
- Target acquisition with varying target density, clutter, field of view, and field of regard
- Vehicle identification with algorithm biased towards threats and imagery degradation
- Land navigation with imperfect waypoints

This paper clearly deserved to win the NMSG Young Scientist Award.

Recommendation: Use this work as a template for future presentations on design of experiments. See summary recommendation 4.b.

3.2 Session 5 – xR Technologies & Applications

Session 5 Chair – Leigh YU (DMSCO, USA)

3.2.1 Paper #10 - Exploiting Virtual Reality Technology in Support of Collective Training for the British Army; David 'Rusty' Orwin, Andrew John Fawkes, Peter Harvey

Paper Abstract: *The British Army's Collective Training Transformation Programme (CTTP) is seeking collective training that is conducted in more dynamic and complex environments (physical, virtual and cognitive). It is developing a Future Collective Training System (FCTS) which includes the aim by 2023 to deploy high fidelity simulation across all Army locations. Pilot studies have been initiated, including an investigation of Virtual Reality (VR) technology. Supported by the UK MoD's Defence Innovation Fund, Bohemia Interactive Simulations (BISim) were selected in December 2018 to conduct an FCTS pilot study into the use of Virtual Reality (VR) in Collective Training to explore the strengths, weaknesses, opportunities, and threats of VR technology and its employment. Over a 3-month period, the pilot considered the effectiveness, fidelity, practicality, architecture, scale, interoperability, infrastructure and mobility of VR. The pilot increased in scale and complexity culminating in 37 players in VR conducting training in a combined arms battle. It also investigated Mixed Reality (MR), cloud technology and training measurement and evaluation. The VR technology showed significant potential in support of collective training and conclusions and recommendations from the pilot are presented including those from the spiral development process.*

Discussion: The presentation began with an overview of a typical training demonstration and an overview of well-known personality aspects of the current warfighter demographic, followed by programmatics. Although they asked for soldier feedback, there was no experimental design or data collection. A suggestion was made to customize avatars' body shapes and movement rather than faces because those are the cues used in field situations. The setup was not well designed, leading to damage to the demonstration environment equipment. NATO has a task looking at advocating for standards that might consider new simulation interoperability standards to support CT VR set up. The presentation erroneously identified HLA as not having an open API while suggesting that commercial solutions do.

Recommendation: Virtual reality has been available, at least experimentally, for at least a decade, and there has been considerable hype about its potential applications. More experimental design and data collection should be performed to measure effectiveness objectively. See summary recommendation 4.b.

3.2.2 Paper #11 - Project Hyper Real Immersion (HRI) - A Partnership Approach to the Development of a Mixed Reality (MR) Capability; Sean Bell

Paper Abstract: *Technology used to provide military forces with their asymmetric advantage; however, the increasing pace of technological advances - particularly in adjacent markets in response to huge investments – is creating new challenges for global military forces. Procurement processes that have matured over decades are well suited to large complex equipment programmes, but are less well suited to exploiting technology, where the pace of change outpaces defence's ability to set requirements, go to competition, down-select, contract award, take delivery and finally get technology into service – by which time the technology is already outdated. In addition, training is a vital ingredient in converting equipment into relevant, credible capability. However, defence is not the market leader in simulation technology, and its procurement processes tend to drive industry to the cheapest compliant solution, rather than incentivising industry to capitalise on adjacent market advances to create a vibrant and evolving training eco-system.*

The UK MOD is pioneering a fresh approach. Through the Defence and Security Accelerator initiative, it has down-selected Close Air Solutions (Project Hyper Real Immersion) and its Mixed Reality capability to be a vanguard project in a co-investment partnership approach to capability development. MOD believes that Project Hyper Real Immersion has the potential to transform the operational training landscape and provide our armed forces the ability to fight as we train– quite the opposite of what our peacetime training model provides today. Rather than waiting for a mature product to be available and then start a lengthy

procurement process, leading to early obsolescence, MOD is exploring the benefits of a partnership approach, through rapid iterative development activity, to inform MOD's future requirements.

Project Hyper Real Immersion is thus exploring not only the potential technological benefits that MR might offer defence in the near future, but also whether a very different relationship with industry is required to capitalise on the technological revolution. This exciting Team UK approach to addressing future Modelling and Simulation requirements could have profound implications for the way modern military forces procure and develop capability; the UK MOD is very keen to collaborate with other nations facing the same challenge.

Discussion: The presentation began with a review of well-known training and procurement challenges and proceeded to a marketing pitch for the presenter's commercial product. NATO and US partners will be invited to participate in the pilot project. The UK MoD is working on changing Joint Terminal Attack Controller (JTAC) Memorandum of Agreement (MOA) accreditation to allow use of VR.

Recommendation: Marketing pitches are probably more appropriate for the show floor at ITEC than for the NMSG annual symposium, especially as this one was labelled as proprietary.

3.2.3 Paper #12 - Immersive Simulation, Prototyping, and Evaluation of Infrared Sensor and Augmented Reality Technologies; John Graybeal, Jacob Quartuccio, Todd Du Bosq

Paper Abstract: *The U.S. Army CCDC C5ISR Center's Night Vision and Electronic Sensors Directorate (NVESD) is tasked with the development of low-light and infrared sensor technologies, which can range in form from air/vehicle mounted sensors, to infantry weapon sensors, and to head-mounted sensors and displays. In this paper, we discuss an immersive testing environment recently acquired by NVESD that is capable of virtual prototyping exercises for different sensor systems, and is likewise capable of serving as an immersive environment examining variations of AR displays and methods of presenting AR information to human operators. The immersive environment consists of a "green room," consisting of plexiglass panels that emit green light via controllable, electroluminescent tape. A pair of cameras, paired with a Vive virtual reality headset (HTC Corporation), are used to form a composite view of real objects and virtual overlays; any object observed in the immersive testing environment is visible to the user, but open green space is replaced by the virtual environment. We describe the new system and simulation use cases for both sensors and AR technologies, describing how such simulation technologies can allow for strict control of empirical scenarios, providing a vigorous evaluation of device characteristics. Ultimately, such simulations will allow Soldiers to experience sensor characteristics and AR displays before the first physical prototype is ever constructed, soliciting valuable user feedback early in the design phase of the acquisition lifecycle.*

Discussion: The presenter began by identifying the shortfalls of non-immersive technologies for prototyping technologies that will be used in a full, live environment. NVESD's "holodeck" is image generator and display agnostic. He illustrated integration of the "holodeck" with a 3D-printed prototype of a proposed sensor. NVESD is working on an experiment of eye-tracking of AR elements vs field of regard because AR elements are expected to be distracting initially. Warfighters haven't reported adverse symptoms after short usage, nor do they see evidence of AR / VR impacting warfighter performance immediately following use, e.g. in flight simulators. The project is researching causes of simulator sickness including gender variance, some of which is device specific. Collectively, the results of the AR Red Team simulations demonstrated that the accuracy thresholds required for AR systems to improve human performance vary as a function of both the specific task itself, and the difficulty of various perceptual judgements within the same task, i.e. distant versus close targets. This is true for any visual task, e.g. detection of people in ghillie suits vs out in the open.

Recommendation: Invite this presenter / project back to discuss the results of these efforts, focusing on experimental design and objective outcomes, as well as lessons learned integrating different technologies into the "holodeck." See summary recommendations 3 and 4.b.

3.3 Session 6 – Architectures

Session 6 Chair – Horst BEHNER (MoD, Germany)

3.3.1 Paper #13 - M&S as a Service (MSaaS): Proof of Concept Development and Integration of a Sensor-as-Service for a Virtual Flight Training Eurofighter Simulation; Daniel Kallfass, Martin Sommer, Stefan Vrieler, Marius Dickebohm

Paper Abstract: The NATO Modelling and Simulation Group MSG-136 "Modelling and Simulation as a Service (MSaaS)" as well as the follow-on MSG-164 "M&S as a Service (MSaaS) Phase 2" targets to develop a service architecture providing rapid deployment of interoperable and credible simulation environments.

This paper presents the results of a proof of concept implementation of an optical and infrared sensor which is realized as a Sensor-as-a-Service. This Sensor-as-a-Service can be provided to other simulators or real operational systems as a lightweight service which can easily be deployed and hosted e.g. on a NATO cloud. As a use case the sensor-as-a-service was integrated into a flight training Eurofighter simulator of Airbus.

Through this proof of concept implementation it was investigated, how a sensor-as-a-service can be designed and hosted on a cloud system and be interconnected with a virtual flight training Eurofighter simulation.

A key issue in infrared image generation is to provide a virtual 3D terrain including multispectral information such as terrain surface types. In this proof of concept demonstration the OGC standard Common Data Base (CDB) was selected. Moving objects are received either through DIS/HLA distributed simulation networks or optionally passed through a service request to the sensor as a service. The sensor parameters like the spectrum, orientation or zoom level can be steered by the virtual Eurofighter cockpit through the service interface.

Discussion: This effort extends the German system demonstrator VIntEL based on the recommendations of MSG-136 and MSG-164, integrating a German Eurofighter virtual cockpit, Common Data Base (CDB)-based synthetic environment service, common operating picture (COP) service, PAXSEM CGF service, virtual sensor service, and a weapon service. The architecture makes extensive use of open, international standards identified in NATO Allied M&S Publication 01 (AMSP-01). They have not yet verified whether containerization improves simulation setup and deployment or reuse, nor do they have a clear recommendation on appropriate granularity of services. Lessons learned for adopting MSaaS include:

- Containers are a mature technology and M&S standards are easy to integrate. But, standards for modularizing functionality are still lacking.
- A business model is needed that works for businesses, users, and developers.
- Decomposing legacy systems is probably not a good idea.

Recommendation: Encourage more sharing of reusable lessons learned such as those above. See summary recommendation 2.

3.3.2 Paper #14 - Development of an Air Operation eXtension with the (Future) C2SIM Standard; Magdalena Dechand, Lukas Sikorski, Irmtrud Trautwein, Bruno Gautreau, Eric Bouvier, Lionel Khimeche

Paper Abstract: The MSG 145 group is working on the Operationalization of Standardized C2-Simulation

Interoperability, side-by-side with the Simulation Interoperability Standards Organization (SISO) Product Development Group (PDG) which is developing the C2 System to Simulation System Interoperation (C2SIM)

standard. The C2SIM standard will improve upon and replace the currently existing combination of Military Scenario Definition Language (MSDL) and Coalition Battle Management Language (C-BML) SISO standards, with a modular approach enabling users of different domains to define their needs in extensions. The main elements of the C2SIM standard are a core logical data model (created as ontology), an extension mechanism, and several extension ontologies (e.g., Land Operation eXtension). The C2SIM standard also supports the transformation of the exchanges (tasking/reporting messages, initialization of C2 and simulation systems) into Extensible Markup Language (XML) schemata.

This paper describes the work done by a French-German subgroup of the MSG-145 to implement a new C2SIM extension for an Air operation domain. The work includes the operational analysis of an Air operation scenario, the design of the logical model with ontologies, the generation of the XML schemata, and their implementation in the systems. This paper concludes with lessons learned, and contributes to the evaluation of the operationalization and the extension of the C2SIM standard.

Discussion: Commission Electronique (COMELEC) is an ongoing French-German project. The presenter provided a brief overview of the relationship between ontologies and schemata. The project illustrates how to add air operations entities to the existing C2SIM core ontology including replacements for both MSDL and C-BML. There are challenges with generating schemata from ontologies, so the PDG agreed to some constraints to achieve a workable standard, e.g. relying on users to use the standard sensibly rather than implementing restrictions. In the future, once the C2SIM PDG has focused on modelling ontologies, they may pursue solutions to the issues identified concerning OWL reasoning features.

Recommendation: See summary recommendation 3.

3.3.2 Paper #15 – A New Simulation Infrastructure Supporting the Next Generation of Simulation-Based Testing and Training Applications; Andreas Tolk, Omar Valverde, Joe Clapis

Paper Abstract: The next generation of simulation systems contains new requirements for simulation infrastructures significantly different from current solutions. Current simulation interoperability standards, such as IEEE 1278 Distributed Interactive Simulation (DIS) and IEEE 1516 High Level Architecture (HLA), are updated on a regular basis by standardisation bodies. Nonetheless, their conceptual frameworks and technical structures are rooted in the last decades' technology and often reach their capability limits when applied to support the most recent system engineering challenges. NATO continues to support and apply these standards, despite them being no longer sufficient to support training, education, and testing of next generation defence systems. We present concepts needed to implement a novel simulation infrastructure, centred around an Information Exchange Services Matrix (IESM) and accompanied by supporting services. This allows the application of new technologies and accommodates the evolution of these technologies in support of composable solutions that provide both "fair fight" training and analysis. These general concepts are applicable to the development of a Joint Simulation Environment (JSE) for the next generation of simulation systems. This paper describes the concepts behind the IESM and their supporting services.

Discussion: The presenter asserted the need for new standards without knowledge of progress being made in existing standards, identification of actual issues, or evidence that their proposal would solve these unknown issues. The proposed schedule to prototype an entirely new infrastructure in two years and have it fully functional in four years is unrealistic given substantial data available on the development time required for existing simulation interoperability solutions. When asked about tackling conceptual modelling and composition, known unsolved problems in M&S, rather than building a new infrastructure that substantially reproduces the functionality of HLA, the briefer asserted a new interoperability solution was required because their problem was constrained to a smaller one than the one solved by HLA.

Recommendation: A more complete, detailed vetting process would eliminate technically inaccurate papers

such as this one. Additionally, this is effectively a marketing pitch for a proprietary architecture that competes with NATO's policy of using open standards.

3.4 Session 7 – M&S Applications

Session 7 Chair – Julie TREMBLAY-LUTTER (DRDC, Canada)

3.4.1 Paper #16 – Virtual Reality CBRN Defence; Johannes Göllner, Andreas Peer, Christian Meurers, Gernot Wurzer, Christian Schönauer, Hannes Kaufmann, Chris Bösch

Paper Abstract: *Over the past decade, training in virtual reality for military and disaster preparedness has been increasingly recognized as an important adjunct to traditional modalities of real-life drills. However, there are only a few existing solutions that provide immersive virtual reality training and improve learning through an increased amount of presence. In this paper, we present a novel and flexible Virtual Reality (VR) training system for military and first responders that enables realistic multi-user training in large environments. We show how the requirements of peer stakeholders for disaster relief with an explicit focus on CBRN disaster preparedness transfer to the concept, current implementation and future features of our system. The development and integration of multiple technologies allows a wide variety of interaction and collaboration within our immersive system. In addition, we demonstrate the training capabilities of our proposed system with a multi-user training scenario, simulating a CBRN crisis. Results from our technical and user evaluation with 13 experts in CBRN response from the Austrian Armed Forces (National Defence Academy & Competence Center NBC Defence) indicate strong applicability and user acceptance. Over 80% of the participants agreed “much” or “very much” that the presented system can be used to support training for CBRN-crisis preparedness.*

Discussion: The paper provided a good survey of previous work in the field which is to be commended. One of the focuses of this effort is cost effectiveness. Automated after action review (AAR) is planned for the prototype. Training was well received by users and trainers, but objective measures of training effectiveness do not appear to have been captured. Experts are needed from the military, commercial industry, and academia to understand the training problem(s) and technologies.

Recommendation: See summary recommendation 3.

3.4.2 Paper #17 – Joint Simulation Environment for United States Air Force Test Support; Timothy Menke

Paper Abstract: *Advances in integrated, multi-domain warfighting capabilities are challenging the ability of militaries to rapidly design, develop, field, support, test, and train next generation war fighting capabilities. Today's physical test ranges, in their present form, are inadequate to meet the testing and training needs of these future integrated weapon systems. Future test capabilities must be augmented with state-of-the-art modelling and simulation technologies to form a virtual range capable of meeting development, test, and training needs in a rapid and cost-effective manner. The United States Air Force, in concert with our Service partners, intends to develop an integrated modelling and simulation based virtual test range to address these challenges. The Joint Simulation Environment (JSE) leverages lessons learned from recent modelling and simulation activities in support of Joint Air Force and Navy testing. JSE seeks to advance the state of the art in modelling and simulation technologies applied to test, training, and experimentation. This paper will discuss JSE use in supporting Air Force objectives, challenges, way-forward, and potential NATO Partnership opportunities.*

Discussion: Standards, interoperability, reuse, and partnering are critical. Live ranges no longer meet testing needs for the Joint Strike Fighter (JSF) due to: geographical constraints, technology limitations, electronic

warfare, frequency spectrum, operational limitations, and safety. Live asset integration has not been levied as a test requirement, but it might be as part of training.

Recommendation: This topic represents an opportunity as a use case for tackling emerging M&S challenges across NATO. See summary recommendation 4.c.

3.4.3 Paper #18 – Integrated Analysis in a Synthetic Battle Space - Lessons from JPOW 2019;
Linda van der Ham, Lesley Jacobs, Hester Vermeiden, Maj. Alexander Mac Lennan,
Lt.Col. Dirk Reinartz

Paper Abstract: *This paper describes the collaborative R&D effort that has been conducted to develop and implement, for the first time in its history, an integrated analysis concept in the Joint Project Optic Windmill (JPOW) exercise series. Since the first edition in 1996, JPOW provides an extensive synthetic battle space - suitable for live-virtual-constructive participation - in which NATO and its coalition partners focus on enhancing interoperability in the Integrated Air & Missile Defence (IAMD) domain by exploring, testing and training future IAMD concepts and solutions.*

The work presented is a joint effort of TNO Defence, Safety & Security, the Royal Netherlands Armed Forces, the German Air Force, and JPOW participants. This paper elaborates on the iterative and multi-disciplinary development and use of several state-of-the art data collection, monitoring, analysis, and visualisation tools enabling both in-situ/real-time data and performance analysis, as well as ‘deep analysis’ in a post-exercise analysis environment such as the Dutch IAMD Battle Lab. In addition, the organisational innovation that is required to successfully implement an integrated analysis concept will be highlighted. Based on lessons which were identified from JPOW19, this paper concludes by depicting the way ahead on how integrated analysis can enhance the effectiveness of synthetic battle spaces for both current and future military operations.

Discussion: The presenter provided an overview of the history and participants in the yearly JPOW exercises. Legacy live systems can still only be stimulated via DIS, not HLA. The 2019 JPOW lessons learned identified the need for deep analysis, e.g. evaluating the effectiveness of design defence on a daily basis. The presenter illustrated the analysis approach and architecture.

Recommendation: See summary recommendation 4.c.

4.0 SUMMARY AND RECOMMENDATIONS

The following is a summary of the presentation by the TER at the end of MSG-171. The items contained here are solely the opinions of the technical evaluator and are not intended to reflect any form of official position.

The opening, invited presentations provided excellent complementary military and civilian perspectives on future challenges for M&S. The organizers are to be commended for selecting papers encompassing all aspects of the theme, Next Generation Synthetic Battlespace.

Recommendations:

1. Several suggestions were made to take a more holistic approach to identifying future NMSG activities which is in keeping with the increasing complexity of integrated M&S and representation of systems of systems. This approach should be encouraged and reflected in a future symposium.
2. One of the key benefits to participants is knowledge acquisition they can apply to their own efforts. In future calls for paper, explicitly request shareable lessons learned and metrics that may help other

participants improve their own efforts. Consider sessions with shorter briefings (15 min.) followed by a panel session where presenters share lessons learned and answer questions from attendees on applying new technologies.

3. Because the topic of the symposium changes every year and presentations are often on work in progress, attendees may not receive the full benefit of the final outcomes of the projects presented. Additionally, the symposium's focus on new and emerging technologies guarantees the topic field is moving very fast, making continuous engagement by attendees highly beneficial. Establish a virtual mechanism to maintain momentum on the topic including follow up detailed questions to presenters where all attendees can view answers, e.g. a wiki or knowledge base. It could also be a mechanism for sharing results of ongoing work.
4. Consider the following for future topics:
 - a. V&V of nascent modelling domains, e.g cyber and HASB, to get out in front of potential problems before there are implementations whose results may not be trustworthy.
 - b. Experimental design for emerging technologies
 - c. Cross-NATO use case challenges, i.e. addressing individual M&S challenges unified by a single use case; this ties in with summary recommendation 1.



Using Behaviour Trees to Model Battle Drills for Computer-Generated Forces

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ABSTRACT

Modelling realistic human behaviour, including decision-making and creativity, is the hardest and most complex challenge in combat simulation. Behaviour trees (BTs) is a relatively new and increasingly popular approach for developing behaviour models for artificial intelligence (AI) and intelligent agents. The approach has become especially popular for creating behaviour models for non-player characters (NPCs) in computer games, robots, and autonomous vehicles.

BTs are represented as directed trees with a hierarchy of control flow nodes and task nodes that control the behaviour of an agent. What makes BTs so powerful is their composability and modularity. Task nodes and control flow nodes are composed into subtrees which represent more complex actions, and these actions can be composed into higher level behaviours.

In this paper we will give an introduction to BTs based on available literature and discuss the possibilities and limitations of employing this modelling technique for creating behaviour models for computer-generated forces (CGF) in combat simulations. Furthermore, we will give a concrete example of how to create a BT from a textual description of a battle drill, and provide tips and tricks on how to create BTs in general. Finally, we will summarize our experiences from working with BTs.

1.0 INTRODUCTION

Modelling realistic human behaviour, including decision-making and creativity, is the hardest and most complex challenge in combat simulation [1]. *Behaviour trees* (BTs) are a relatively new and increasingly popular approach for developing behaviour models for artificial intelligence (AI) and intelligent agents. The approach has become especially popular for creating behaviours for non-player characters (NPCs) in computer games, robots, and autonomous vehicles. The first high-profile computer game that used BTs was Halo 2 from Bungie Software [2], which was released in 2004.

Finite state machines (FSMs) have long been the most dominant technique for creating behaviour models for computer-generated forces (CGF) in military simulations [3][4], but BTs are now also starting to become a popular technique for developing behaviour models for automated and semi-automated constructive units in military simulation systems. FSMs are well suited for implementing well-defined doctrinal behaviour of limited complexity [4]. However, the problem with FSMs is that they tend to become very complex and unmanageable. The reason for this is that the number of states increases exponentially with the number of non-mutually exclusive behaviours that are represented [5][6], and as the number of states increases, the number of possible transitions between the states also increases exponentially [7].

BTs have some similarities to hierarchical FSMs, but the key difference is that their main building blocks are *tasks* rather than *states*. BTs are represented as directed trees¹ with a hierarchy of control flow nodes and task nodes that control the behaviour of an agent. The control flow nodes are interior nodes (nodes with one or more children) and contain some decision logic for flow control. The task nodes are leaf nodes (nodes without children) and contain conditional tasks which test some property in the simulated environment (or the real world in the case of robots and autonomous vehicles), or action tasks which alter the state of the simulation (or the real world) in some way [5].

What makes BTs so powerful is their *composability* and *modularity*. Task nodes and control flow nodes are composed into subtrees which represent more complex actions, and these actions can be composed into higher level behaviours [8]. Task nodes and action subtrees can be reused, and different subtrees can be developed independently of each other.

BT editors with graphical user interfaces (GUIs) enable users (e.g. military simulation users) to create modular behaviour models without needing programming skills. Furthermore, to reduce complexity and ensure readability of the graphical model of large BTs, they can be decomposed into smaller subtrees. Examples of AI engines (or AI middleware) for military simulation systems that use BTs are Virtual Battlespace (VBS) Control from Bohemia Interactive Simulations (BISim) and MASA Life from MASA Group.

We conduct entity-level, constructive simulations of battalion- to brigade-level operations for experimentation and analysis purposes [5][9][10]. To support this work we are developing human behaviour models for semi-automated forces (SAF) in VBS, using the new AI framework VBS Control.

Since BTs are a quite new technique for developing behaviour models, there is still not very much documentation on how BTs work and how to create BTs. Most BT tutorials found on the Internet focus only on the basic principles of BTs, and how to implement BT functionality in an AI engine, but there are few examples on how to create working BTs.

First, in this paper, we briefly describe the background for this work. Secondly, we give an introduction to BTs and look at the process of developing BTs. Then, we look at the advantages and limitations of BTs and some of the extensions to the BT concept that have been proposed. After this, we describe how we are using BTs to build a library of behaviour models of battle drills for mechanized infantry platoons and give a concrete example of how to create a BT from a textual description of a battle drill. Finally, we summarize our experiences from working with BTs and outline our plans for further work.

2.0 BACKGROUND

At the Norwegian Defence Research Establishment (FFI) we conduct simulations of land force operations for experimentation and analysis purposes. One of the main research questions we are investigating is *how to increase combat effectiveness in land force operations*, and as part of this work we assess and compare the performance of different land force structures, which may vary with regard to: *composition of material and equipment, tactical organization, or operational concept*. Our simulation experiments are conducted as what can be described as *simulation-supported, two-sided* (Blue and Red) *wargames*, where military officers participate as players/operators on both sides [5][9][10].

Based on previous simulations, we have identified two main factors that have the potential to improve the fidelity of our constructive simulations: (1) *increased terrain resolution*, and (2) *better tactical artificial intelligence* (AI) that can take advantage of this terrain [5][9][10]. For example, we expect that these two factors will result in more realistic detection and engagement distances in our constructive simulations

¹ Strictly speaking, a BT is a *directed acyclic graph* (DAG) since the same node or subtree can be used several places in the structure, and a node can thus have more than one parent.

[9][10]. Furthermore, since we are using constructive simulation to experiment with utilization of new technologies and new concepts on the battlefield, we need an easy way to make changes to behaviour models for experimenting with different tactical behaviours of entities and platoons. The composability, modularity, and readability of BTs make this modelling technique very suitable for our use.

We have composed a simulation environment where the ground-to-ground combat entities are simulated in VBS from BISim, and the air and air defence entities are simulated in VR-Forces from VT MAK. All the constructive, semi-automated entities are controlled from an in-house developed web-based graphical user interface (GUI), which has been named webSAF [9][10]. The entities simulated in VBS use behaviour models developed in VBS Control. VBS Control is a new framework for BT-based AI in VBS. To get better tactical AI in our simulations, we are currently building a BT-based library of behaviour models for the most important battle drills for mechanized infantry platoons.

3.0 INTRODUCTION TO BEHAVIOUR TREES

BTs are a relatively new technique for developing behaviour models. Nevertheless, BTs have reached a certain maturity and have been treated in at least two Game AI textbooks [8][11]. Furthermore, a number of BT tutorials can be found on the Internet. The available descriptions of BTs differ slightly, and a suggested unified framework for BTs was published in 2014 [12].

3.1 Structure

BTs are graphically represented as *directed rooted trees*. Directed rooted trees are composed of *nodes* and directed *edges* connecting the nodes. Trees cannot contain any cycles. For a pair of connected nodes, the outgoing node is called the *parent*, and the incoming node is called the *child*. A parent node has one or more children. Rooted trees have one parentless node that is called the *root*. Nodes without children are called *leaves*. In BTs the edges are directed away from the root and towards the leaves. BTs are usually drawn with the root at the top, and the children are usually ordered from left to right.

3.2 Traversal

A BT represents all the possible courses of action an agent can take, and a path from the root to one of the leaf nodes typically represents one possible course of action [8]. BTs are essentially traversed in a *depth-first* manner (from left to right). Starting from the root, the leftmost children are visited first until a leaf node is reached, before backtracking and visiting the next child (to the right) of the nearest node with more children.

An AI engine will usually traverse a BT from the root for each *simulation step* or *tick*, executing each node down the tree. The simulation step or tick may correspond to the frame rate of the simulation, but can also be longer. The simulation step represents the maximum time it will take for the behaviour model to detect, and be able to react to, a change in the environment. For a model representing human behaviour this should not be longer than a typical human reaction time (usually between 0.2 and 0.4 seconds).

During the traversal of a BT each executed child node will return one of the following three status values to its parent:

1. *Success*: The node achieved its goal.
2. *Failure*: The node failed.
3. *Running*: The node did not finish its execution within the current simulation step and is still running.

The running status is typically returned by tasks that take some time to complete, for example moving from one place to another.

Each time a BT is executed it either finishes by returning success or failure back to the root node, or the execution ends up in a node representing a task that takes some time to execute and thus is still running at the end of the simulation step. At the next simulation step, the AI engine can either be designed to continue the BT execution at the leaf node that returned running, or more commonly, to restart the BT execution at the root. Starting at the root at each simulation step allows the behaviour model to be more reactive to context changes, which is an important property in dynamic environments. Of course, if there are no context changes the BT execution will end up in the node that returned running at the previous simulation step and continue the execution of this task.

3.3 Types of Nodes

The main categories of nodes in a BT are *control flow nodes* (or *composite nodes*), *task nodes* (or *execution nodes*), and *decorator nodes*. In addition, a BT can have *reference nodes*, which are just references to a subtree.

3.3.1 Control Flow Nodes

The control flow nodes are the interior nodes in a BT, and they always have one or more children. There are three types of control flow nodes: *selector nodes*, *sequence nodes*, and *parallel nodes*.

3.3.1.1 Selector Nodes

A selector node² will start to execute each of its children from left to right and return success as soon as one of the children returns success. If none of the children returns success, the selector node will return failure. If the child that is currently being executed returns running at the end of a simulation step, the selector node will return running. Figure 3-1 shows the graphical representation of a selector node with N children. The selector node is denoted by a question mark (?).

Selector nodes are typically used when a set of actions represents alternative ways of reaching a goal. Some BT implementations also define *non-deterministic* or *random* selector nodes, where the children are executed in a non-deterministic order.

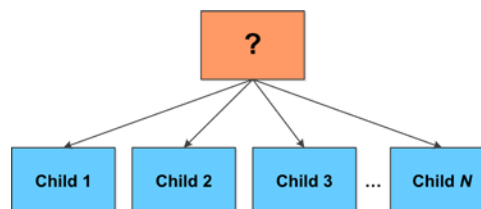


Figure 3-1: Graphical representation of a selector node with N children.

3.3.1.2 Sequence Node

A sequence node will start to execute each of its children in sequence from left to right and return failure as soon as one of the children returns failure. If all the children return success, the sequence node will return success. If the child that is currently being executed returns running at the end of a simulation step, the

² Selector nodes are sometimes called fallback nodes.

sequence node will return running. Figure 3-2 shows the graphical representation of a sequence node with N children. The sequence node is denoted by a rightwards arrow ($\rightarrow$).

Sequence nodes are typically used when a set of actions needs to be carried out in a particular order. Some BT implementations also define non-deterministic sequence nodes, where the children are executed in a non-deterministic order.

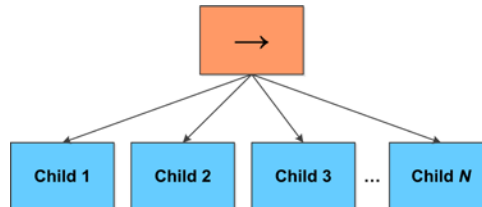


Figure 3-2: Graphical representation of a sequence node with N children.

3.3.1.3 Parallel Node

A parallel node will execute all of its children in parallel. If one child returns failure, the parallel node will return failure and terminate the execution of all the other children. If all the children complete successfully, the parallel node will return success. If none of the children have returned failure, and one or more children return running at the end of a simulation step, the parallel node will return running. Figure 3-3 shows the graphical representation of a parallel node with N children. The parallel node is denoted by rightwards paired arrows ($\Rightarrow$).

Parallel nodes are typically used when a set of actions can be carried out at the same time. Some BT implementations define parallel nodes with different criteria for success, for example return success if more than M out of N children return success, or only return failure if all of the children return failure.

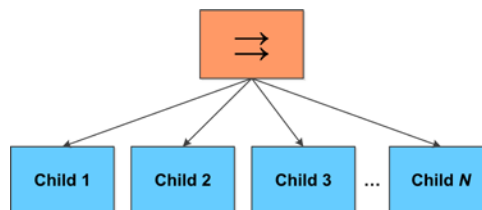


Figure 3-3: Graphical representation of the parallel node.

3.3.2 Task Nodes

The task nodes are the leaf nodes in a BT. There are two types of task nodes: *condition nodes* and *action nodes*.

3.3.2.1 Condition Nodes

A condition node checks if a given condition within the simulated environment (or the real world) is fulfilled. If the condition is fulfilled it returns success, otherwise it returns failure. A condition task will always complete within a simulation step, so this task will never return running. Figure 3-4 (to the left) shows the graphical representation of the condition node. The “Condition” text label will typically be a description of the condition.



Figure 3-4: Graphical representation of the condition node (to the left) and the action node (to the right).

3.3.2.2 Action Nodes

An action node performs an action which alters the state of the simulated environment (or the real world) in some way. If the action was completed, the action node will return success, and if the action could not be completed, the action node will return failure. Running will be returned if the action was not finished within the current simulation step. Figure 3-4 (to the right) shows the graphical representation of the action node. The “Action” text label will typically be a description of the action.

3.3.3 Decorator Nodes

A decorator node is a special type of node that has only one child and modifies the behaviour of the child according to some predefined rule. Examples of decorators are *inverter* nodes that invert the result from the child (i.e. success to failure and failure to success), *succeder* nodes that always return success, and *repeater* nodes that repeat the execution of the child a specific number of times or until a given condition is fulfilled. A BT can have several subsequent decorators. Figure 3-5 shows the graphical representation of the decorator node. The “Decorator” text label will typically be a description of the rule of the decorator.

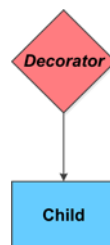


Figure 3-5: Graphical representation of the decorator node and its child.

3.3.4 Reference Nodes

A reference node is simply a proxy node that refers to a particular subtree. A particular subtree may be used several places in a BT.

3.3.5 Summary of Node Types

Table 3-1 summarizes the properties of the different types of nodes in a BT.

Table 3-1: Properties of the different types of nodes in a BT.

Node type	Symbol	Success	Failure	Running
Selector	?	If one child returns success	If all children return failure	If one child returns running
Sequence	→	If all children return success	If one child returns failure	If one child returns running

Parallel	$\Rightarrow$	If all children return success	If one child returns failure	If one or more children return running (and none of the children have returned failure)
Action	<i>Text label</i>	If action was completed	If action could not be completed	If action is still running
Condition	<i>Text label</i>	If condition is fulfilled	If condition is not fulfilled	Never
Decorator	<i>Text label</i>	According to rule	According to rule	According to rule

3.4 Data Store

What makes BTs highly modular and flexible, is the concept of having a single common interface for all nodes. This allows that any task or subtree can be placed at any position in the BT. For this to work, the data used by the BT needs to be decoupled from the interface between the nodes. This is usually done by having an external data store, called a *blackboard*, for all the data that the BT needs.

3.5 Performance

The performance of a BT will depend on the complexity of the task nodes. If we assume that the task nodes (leaf nodes) are of $O(1)$ in both performance and memory usage³, the average performance for a BT will be of $O(\log n)$ and the memory usage for a BT will be of $O(n)$, where n is the number of nodes in the BT [8].

4.0 DEVELOPING BEHAVIOUR TREES

Development of BTs is an iterative process, where we typically start with a simple BT and then make it more complex by adding more and more branches of alternative courses of action for achieving a goal. Generally, in a BT, the left branch of the tree (starting from the root) will contain the high-priority behaviours, while the right branch of the tree will contain the low-priority behaviours. The default or unconditional behaviour will therefore be found at the far right side of a BT.

An important question when designing a BT is what functionality to address in the BT structure, and what functionality to take care of inside the action nodes [13]. Generally, most modularity is achieved if each task can be broken into the smallest parts that can usefully be composed [8]. However, a BT that is too fine grained may be unnecessarily complex [13]. As a rule of thumb, a BT should be decomposed into the smallest action nodes which do not have subparts that are likely to be usable as stand-alone actions in other parts of the BT.

Developing and editing BTs are mostly done using visual editors, but BTs can also be automatically generated from examples of expert behaviour by using machine learning techniques [14][15].

4.1 Examples

4.1.1 Example 1: Move into Room (Simple)

Figure 4-1 shows an example of a simple BT for moving into a room. When this BT is executed the selector node will first try to execute the left child, which is a sequence node. The sequence node will first execute the condition node, which checks if the door is open. If the door is open, the sequence node will execute the

³ O notation (O stands for order) classifies algorithms according to how their running time or memory requirements grows as the number of elements processed by the algorithm grows.

next child, which is an action node that moves the agent into the room. If the door is closed, the sequence node will return failure, and the selector node will try to execute the right child, which is also a sequence node. This sequence node will try to execute the following three action nodes: “Move to door”, “Open door” and “Move into room”. If any of these three action nodes fails, the whole BT will return failure.

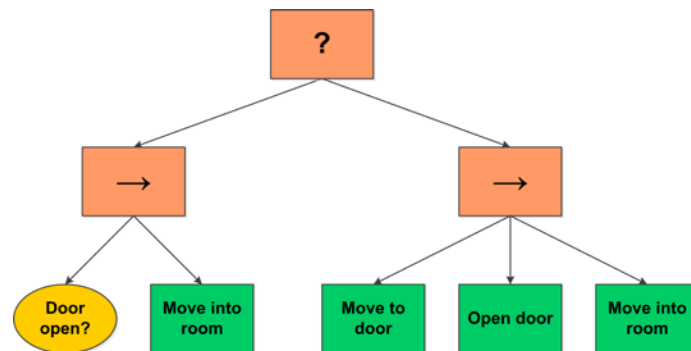


Figure 4-1: Simple BT for moving into a room.

4.1.2 Example 2: Move into Room (More Advanced)

Figure 4-2 shows a slightly more advanced BT for moving into a room. Here the “Open door” action node from Figure 4-1 has been extended to a subtree starting with a selector node. This selector node will first try to execute the left child, which is a sequence node. The sequence node will first execute the condition node, which checks if the door is locked. If the door is locked, the sequence node will execute the next child, which is an action node that unlocks the door. If the sequence node fails, the selector node will try to execute the right child, which is also a sequence node. This sequence node will try to execute the action node “Kick door”, and then execute a condition node which checks if the door is now open.

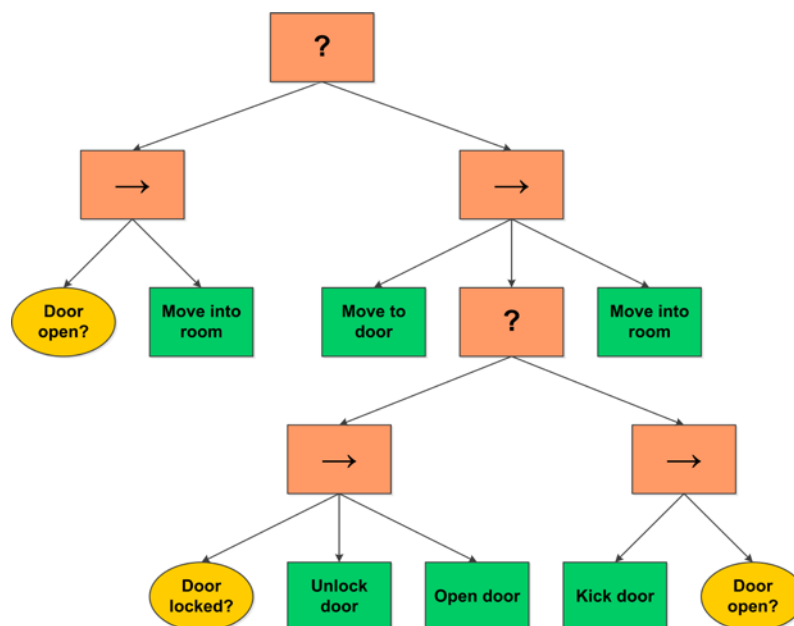


Figure 4-2: More advanced BT for moving into a room.

5.0 ADVANTAGES, LIMITATIONS AND POSSIBLE EXTENSIONS OF BEHAVIOUR TREES

In AI research BTs are classified as a simple form of planning referred to as reactive planning [8]. To be reactive means to be able to quickly react to changes. Behaviour models using reactive planning techniques are suitable for handling highly dynamic and unpredictable environments, such as a modern battlefield.

From a theoretical point of view, there is no difference between BTs and FSMs regarding what kind of behaviour that can be modelled [12]. In practice however, whereas FSMs tend to become impractical and unmanageable as the complexity of the behaviour model grows, complex BTs are much easier to maintain and extend.

5.1 Advantages

The most important advantages with BTs can be summarized as follows:

- BTs are highly *composable*. Composability means the ability to combine components into various combinations for building different systems.
- BTs are highly *modular*. That a system is modular means that it can be subdivided into modules (tasks or subtrees for BTs), and that any module in the system can be replaced by any other module. This also means that the modules can be developed independently of each other.
- BTs are *reactive*, which means that they can react quickly to changes.
- BTs are *human readable* and can be created by visual editors with GUIs.
- BTs are suitable for *automatic generation*, for example by using machine learning.

All these properties make BTs well suited for developing human behaviour models of moderate complexity for semi-automated forces (SAF) in constructive simulations.

5.2 Limitations

The most important limitations of BTs can be summarized as follows:

- BTs are poor at modelling the uncertainty in situations where there are multiple valid options to choose from [11].
- It is somewhat cumbersome to represent typical state-based behaviour using BTs [8].
- There are limitations on how large and complex behaviour models can be when using BTs. For very large BTs, the cost of having to execute the whole tree from the beginning for each simulation step will eventually cause performance issues, especially in simulations with a high number of constructive entities.

5.3 Possible Extensions

To overcome the limitations of standard BTs, several extensions have been proposed. The first limitation is mainly related to the properties of the selector node. One simple way to vary the order in which the selector node executes its options is to introduce non-deterministic selector nodes. This will lead to more unpredictable behaviour. A more comprehensive way to address this limitation is to combine BTs with utility-based decision-making, as suggested in [16]. Here, a utility selector node is introduced, which when executed first queries all of its children for a utility value, and then uses these values to determine in which order the children will be executed. The calculation of utility values must typically be done by the task

nodes, and then propagated up the tree structure. This method will, however, require additional computing power for each simulation step.

A simple solution which will overcome the second limitation is to combine BTs with FSMs [8]. Instead of having one large BT representing all the possible behaviours of an agent, it will then be possible to have different context-sensitive BTs for each of the states the agent can be in, and a simple FSM on top that handles the transitions between the states.

The limitation regarding performance issues with large BTs is harder to solve without compromising the reactivity of the BTs. To avoid unwanted re-execution of all control flow nodes for each simulation step, control flow nodes with memory have been suggested. The control flow nodes with memory will then remember what value each child has returned, and avoid re-executions of the children until the whole control flow node has returned success or failure [13]. This approach will, however, make the BT less reactive, and will therefore not be suitable for use in dynamic and unpredictable environments.

6.0 BUILDING A LIBRARY OF BEHAVIOUR MODELS OF BATTLE DRILLS

As mentioned, to get better tactical AI in our simulations, we are currently building a BT-based library of behaviour models of the most important battle drills for mechanized infantry platoons, including dismounted soldiers and combat vehicles like infantry fighting vehicles (IFVs) and main battle tanks (MBTs). The behaviour model library will have a hierarchical structure with models of battle drills for entities, squads, and platoons for dismounted soldiers, and entities and platoons for combat vehicles. Human operators will give orders to the semi-automated forces (SAF) at the squad or platoon level, but we want the entities to be completely autonomous within a squad for dismounted soldiers and within a platoon for combat vehicles. In the future, we envisage building behaviour models for a set of more generic battle drills at the company level, so that more general orders can be given at this level. It is a goal that one operator should be able to control an entire battalion of manoeuvre forces.

The workflow for creating the behaviour models follows a bottom-up approach, where we first model a set of low-level actions that the simulated entities should be able to execute. These actions are typically represented as action nodes. From the low-level actions we compose subtrees representing more complex actions or tasks for the individual entities, and these are further used to build BTs of battle drills for the entities. Typically, much work is required to create the first BTs, but as the library grows, it is more and more likely that it is possible to reuse already built subtrees when building new BTs.

In addition to the BTs for the individual entities, we build BTs for battle drills at the unit level for squads and platoons. The unit level behaviour models coordinate the behaviour of the individual entities and issue orders (i.e. assigns BTs) to the entities. The unit level behaviour models thus represent the leading element of the unit. Messages are used for communication between the unit level BT and the entity level BTs, for example for sending orders from the unit level BT to the entity level BTs, and sending reports from the entity level BTs to the unit level BT. The same principle is used to build additional levels of behaviour models. For example for infantry, we have behaviour models at the entity level, squad level, and platoon level. In principle there are no limitations on the number of levels of BTs that can be modelled in VBS Control, and in the future we also plan to build BTs at the company level. Figure 6-1 illustrates the hierarchy of behaviour models.

To get an overview of the different tasks a unit should be able to carry out, it is possible to use so called Universal Task Lists (UTLs). Detailed descriptions of tasks and battle drills can often be found in field manuals and of course by consulting subject matter experts (SMEs) and officers. At the unit level we build BTs corresponding to the orders that can be issued by the human players/operators. Figure 6-2 shows an example of orders that can be issued to generic combat vehicle platoons. The orders are categorized as

“Offensive”, “Defensive” or “Move”. For our simulation-supported, two-sided wargames we need to create models of battle drills for both Blue and Red forces, since they usually follow different doctrines.

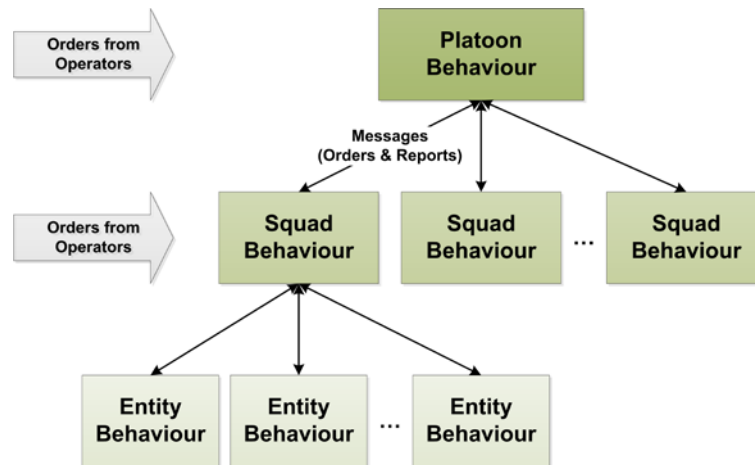


Figure 6-1: Hierarchy of behaviour models.

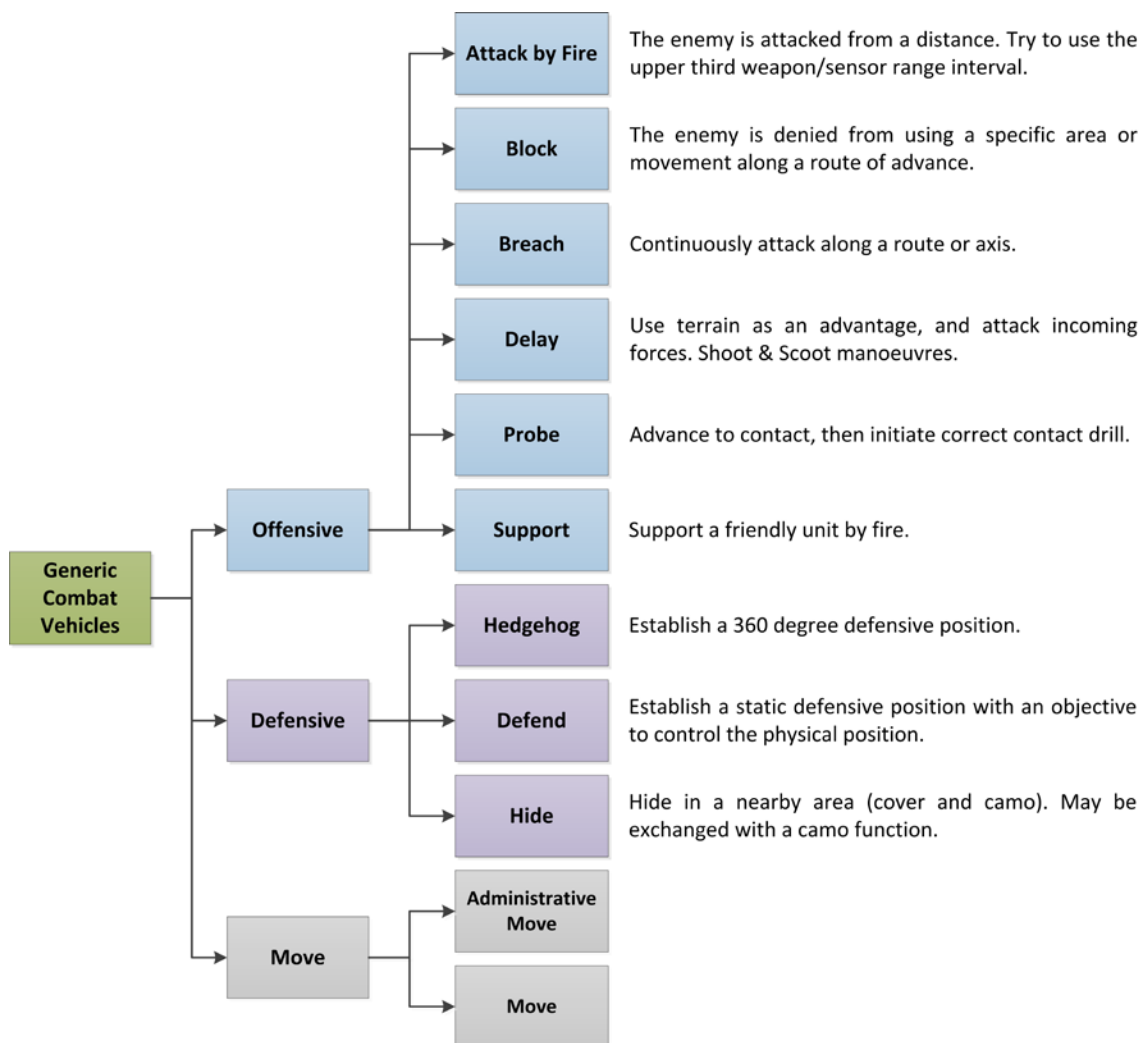


Figure 6-2: Example of orders for combat vehicle platoons.

6.1 Example: Model of a Contact Drill for an Infantry Squad

In this subsection we will first give a short description of a battle drill for enemy contact for a dismounted infantry squad. The contact drill has been taken from an unclassified Norwegian field manual for dismounted infantry squads [17]. After this we will look at the modelled squad level and entity level BTs for the contact drill.

Description of contact drill:

1. Soldier 1 (scout) discovers the enemy in front, fires a burst and keeps firing rapid single shots while shouting “Contact front!” and seeking cover. This is illustrated in Figure 6-3 (a).
2. Soldier 2 (squad leader) moves to the right (or left), provides covering fire, and shouts “Covering!”. At the same time the rest of the squad forms a line to the left (or right) of Soldier 2. This is illustrated in Figure 6-3 (b).
3. As soon as Soldier 1 is covered by Soldier 2, he or she starts to withdraw to a new position. Soldier 1 and Soldier 2 conduct backwards leap-frogging, while the others find positions and fire a burst followed by single shots. This is illustrated in Figure 6-3 (c).
4. Soldier 1 and Soldier 2 pass Soldier 3 on their way backwards, and the squad will split into two fire-teams. Fireteam 1 moves collectively backwards to new positions while Fireteam 2 provides covering fire. Afterwards, Fireteam 2 moves backwards to new positions while Fireteam 1 provides covering fire. This is illustrated in Figure 6-3 (d).
5. The leap-frogging continues until they find a position where they can break off contact, and the squad can find cover and concealment from the enemy. The squad then forms a line and moves towards the cover. This is illustrated in Figure 6-3 (e).

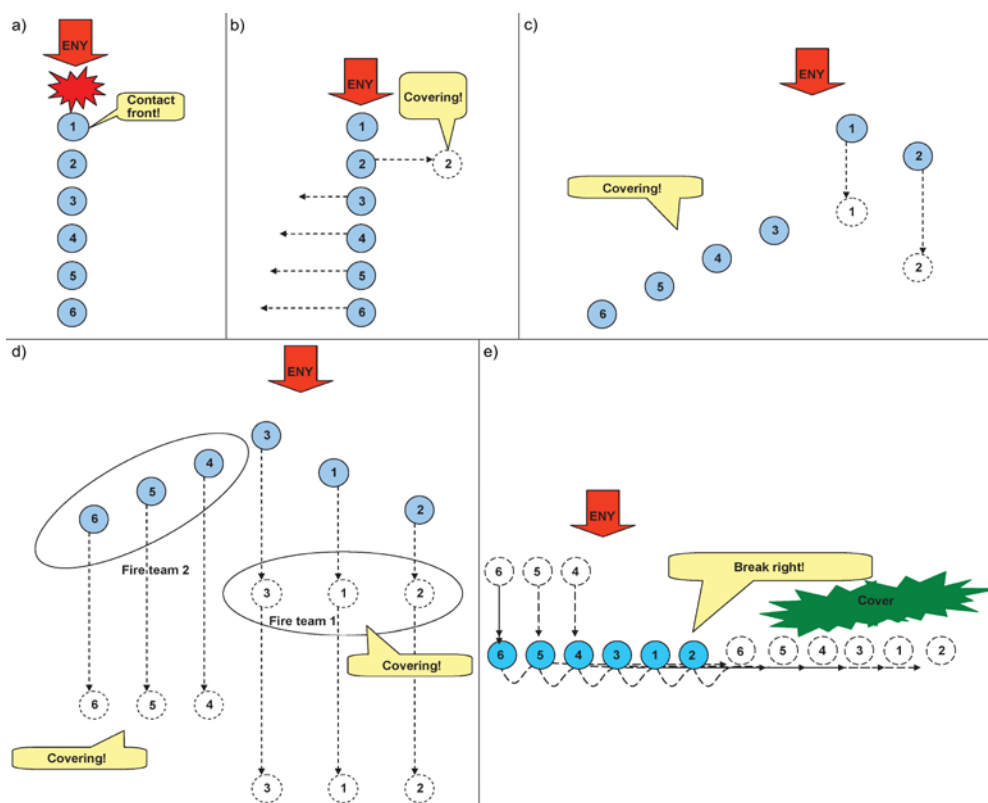


Figure 6-3: Battle drill for enemy contact for a dismounted infantry squad ([17]).

6.1.1 Modelled Behaviour Trees for Contact Drill

Figure 6-4 shows the modelled BT for the squad, and Figure 6-5 shows the modelled BT for the first soldier in the squad (Soldier 1). The squad BT for the contact drill will typically be used as a subtree in a BT for a squad move order.

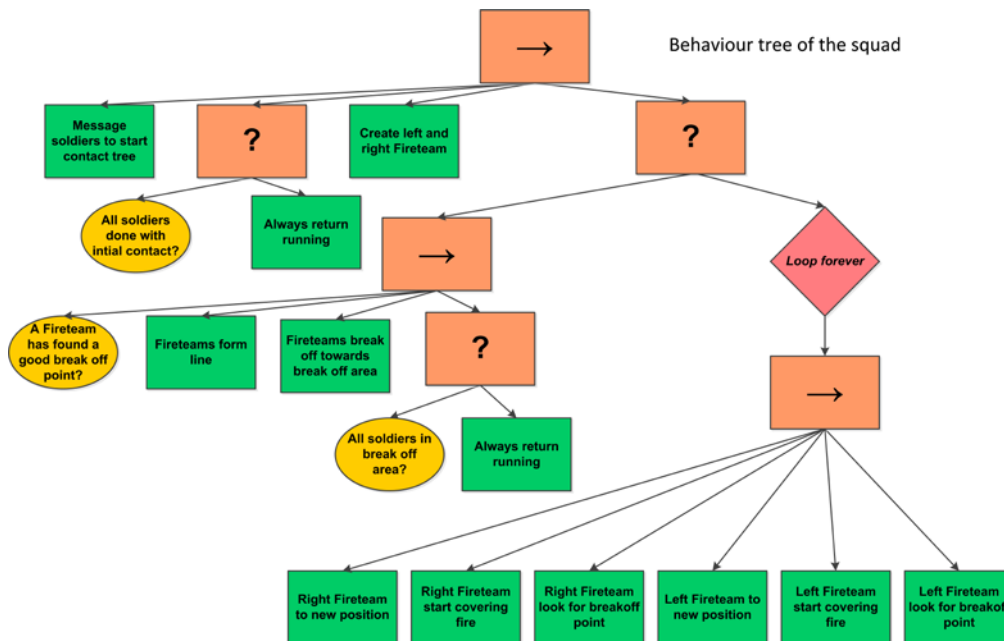


Figure 6-4: Squad level behaviour tree for the contact drill.

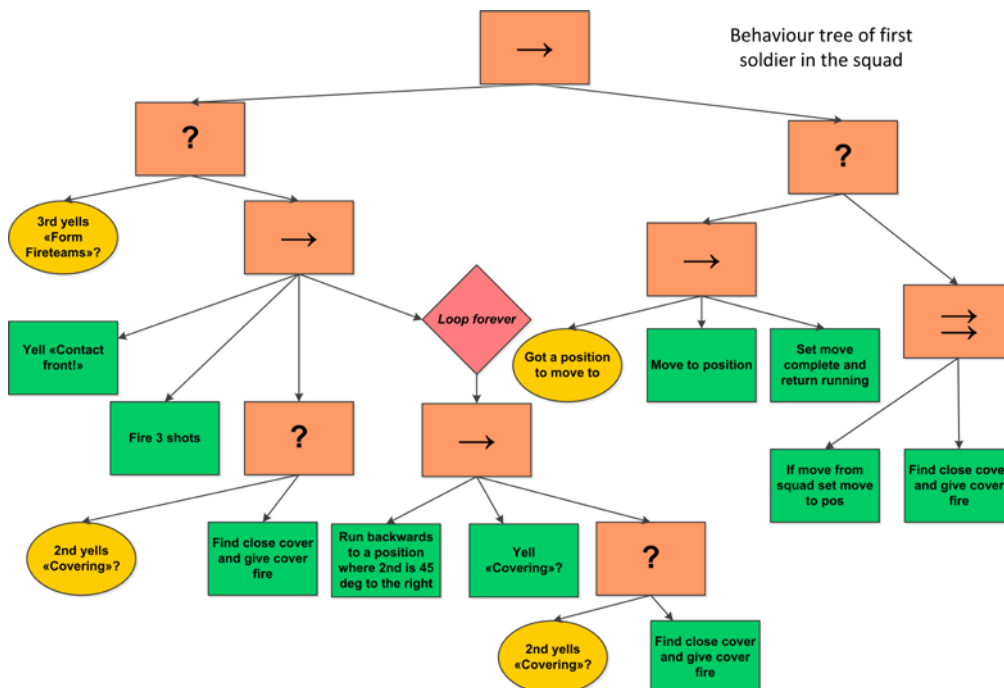


Figure 6-5: Behaviour tree for the contact drill for the first soldier in the squad (Soldier 1).

7.0 EXPERIENCES

We have been working with BTs for about three years. The first year we mostly explored and tested out the approach, but for the last two years we have systematically developed BTs for battle drills. BTs have a somewhat steeper learning curve than for example FSMs, and it takes some time to become familiar with how the control flow nodes work. We found that hands-on experimentation with different control flow patterns was very useful to better understand how BTs work, and how to create good BTs.

The experiences with using BTs to develop behaviour models have so far been very good. Especially the composability and modularity that enables subtrees to be reused is very useful and simplifies the development process. Often we start by building an initial subtree for an action, and then reuse this in multiple places. Later, when we improve the subtree, this improvement will apply to all BTs that use this subtree.

A good visual editor is very helpful for creating BTs. Visual editors let the user rapidly visualize the flow of the behaviour and easier understand how the behaviour works. We use the VBS Control Editor, which also has a built-in debugger that lets the user add breakpoints and run through a BT step by step while the behaviour model is executed in VBS. This functionality is very helpful for pinpointing the source to why the entities sometimes do not behave as intended.

We have found it to be advantageous to have a separate BT handling the internal coordination of a unit, which is not tied to a specific entity (or subunit). This way, for example, all the soldiers in a squad can have the same BT, and it is not necessary to have a specific BT for the squad leader. This system also makes it easier to handle casualties, and the unit will still function if the squad leader is killed.

One challenge we have found with using BTs, is handling unexpected jumps in the execution of a BT. An entity can be doing something specific far down in the tree structure, and then suddenly something fundamentally changes about the situation and a very different subtree starts executing instead. When this happens, it is important that the entity is reconfigured for the new situation. It is good practice, at the start of a subtree, to always make sure things are configured correctly before continuing and not assume anything was correctly configured before.

It is also worth mentioning that the composability and modularity of BT-based behaviour models open up opportunities for collaboration on development and sharing of behaviour models of battle drills, for example between NATO and partner nations, that mostly have similar doctrines.

8.0 FURTHER WORK

A lot of work remains before the library of behaviour models of battle drills is complete. The behaviour models also need to be validated, and this will typically be done by face validation by military SMEs and officers from the Norwegian Army. Furthermore, the behaviour models will be continuously subjected to face validation by the players/operators when they are used in our simulations, and in the beginning we expect that the models have to be continuously improved based on feedback from the players.

We have demonstrated the behaviour models for officers from the Norwegian Army at several occasions, and the feedback we have received is very positive. The Norwegian Army has expressed interest in the possibility of using the behaviour models in other simulation systems that support BTs as well. To make this possible we need to ensure that the models also exist as conceptual models that can be implemented in other simulation systems. The BTs in Figure 6-4 and Figure 6-5 are examples of such conceptual models. The parts of the models that typically need to be implemented specifically for each simulation system are the task nodes (i.e. the leaf nodes in the BTs).

We are primarily developing behaviour models for pure constructive simulations with SAF. This generally sets lower requirements for how high fidelity the behaviour models for the entities need to have, compared to behaviour models for constructive entities that are meant to be used together with virtual entities directly controlled by humans. This is an issue we may also need to address in the future, since it may be desirable for us to combine virtual and constructive simulations.

9.0 SUMMARY AND CONCLUSION

This paper has given an introduction to behaviour trees (BTs), discussed advantages and limitations of BTs, and described how we use BTs to build a library of behaviour models of the most important battle drills for mechanized infantry platoons. BTs have become very popular, especially for creating behaviours for NPCs in computer games, robots, and autonomous vehicles, mainly because they are composable, modular, and reactive. These properties also make BTs well suited for developing human behaviour models of moderate complexity for semi-automated forces (SAF) in constructive simulations.

Our experiences with using BTs to develop behaviour models have so far been very good. However, a lot of work still remains before our library of behaviour models of battle drills is complete.

Finally, the composability and modularity of BT-based behaviour models open up opportunities for collaboration on development and sharing of behaviour models of battle drills, for example between NATO and partner nations that mostly have similar doctrines.

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Computer Modelling of Human Populations in Support of Military and Civil Command and Control (C2) Exercises

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ABSTRACT

This paper discusses the design of a computer modelling framework for a UK military training and education requirement, lessons learned during its construction and implications for representing the complex and contested future operating environment.

The "Influence and Infrastructure Combat Model" (IICM) is a computer simulation that models the flow of information and resources through a Human Terrain and the supporting critical national infrastructure networks (CNI). This project began as a study on methods of modelling the effects of Cyber activities on a local population and was extended to include wider military actions including Hybrid, Military Operations in Urban Areas (MOUT) and Informational Manoeuvre activities.

IICM treats the population as an unstable equilibrium destabilised by external actors. Drawing upon group dynamics theory and epidemiological compartment modelling techniques, information is modelled as mimetic packets which are passed between software agents representing population groups, changing the level of support for different factions. These act as a quantifiable 'target' for influence operations within an exercise.

Drawing on our experience in military exercising, IICM is designed to operate as an independent model or federated with a kinetic warfare simulation. It presents effects as seen by the military decision maker, rather than the low-level analyst or system operator.

1.0 COMMAND AND CONTROL EXERCISES

The Contemporary Operating Environment (COE) is characterised by complex terrain, pockets of high population density and adversaries that seek to engage our forces over multiple domains, physical and virtual. Critical decisions may need to be taken on limited and incomplete information.

Command and Control (C2) exercises test the ability of a command group to assimilate information, make decisions, implement a resultant course of action and observe a potential outcome. These exercises often substitute computer generated forces operating in a synthetic environment for live forces, saving time and material.

The current generation of Modelling and Simulation (M&S) tools struggle to simulate the COE at the level perceived by a unit commander and his support staff. To be effective, a COE model must understand both the current range of effectors (kinetic attack, influence activities and cyber warfare) and the potential targets of action (regular and irregular military forces, and the civil population). A significant part of this

requirement is the mood (sentiment) of a local population and its reaction to military forces and information operations

1.1 Current Training Solutions

Current solutions use two different classes of model to represent the battlespace.

- Kinetic warfare models represent the physical world along with the principle military combat units. Time, distance and firepower are key concepts. Human factors are often downplayed to allow the training audience to concentrate on the coordination of physical activity between different units.
- Sociological and Human Terrain models perceive the world in terms of human activity and social linkages. Concepts like geography and time are often highly approximated, allowing a greater focus on information flows through a population. Most models require complex (and expensive) start data and exhibit a wide range of outcomes to small changes in the input orders.

Since they are based on different underlying concepts, integrating the results between Kinetic and Sociological models requires manual processes, often impractical in the timescales and budgets available on training events. Furthermore, these processes are susceptible to unconscious human bias on the part of exercise control and the training audience, reducing confidence in the outcomes and leading to disengagement of the training audience.

2.0 HUMAN TERRAIN REQUIREMENT

In 2017, NSC led a UK project investigating Defensive Cyber Concepts by researching methods of modelling the effects of Cyber Warfare on human and infrastructure networks. This resulted in a report "Dynamic modelling of infrastructure and human networks" (Athena DSTL Project Number 707354).

This report concluded that current population modelling techniques are too expensive to support training events, especially those that include Influence Operations. A requirement was identified for a specialised Human Terrain model designed to support the needs of military exercises and educational tasks.

The report observed that the Human Terrain is a contested domain whose background equilibrium can be disturbed by routine day-to-day military activity in a region, as well as overt Informational Manoeuvre operations. Operations by military and civil forces (including Cyber Warfare) can lead to unintended collateral effects that destabilise components of the Critical National Infrastructure, which in turn affect the ability of the local population to go about their daily activity, and so upset a local balance of power amongst that population.

Several key factors need to be addressed in a potential model:

- The model must work with both real world and fictional scenarios. Since pre-existing fictional scenarios have little or no supporting Social Media data (a common source dataset for existing Human Terrain models), the models will need to use an alternative data source.
- The model output must be comprehensible by a non-specialist training audience as well as an analyst. To further audience understanding, chaotic population behaviour must be constrained, even when this is present in real world scenarios.
- To allow the complete range of HQ functions to be exercised on the same event, the model must link to existing Kinetic Warfare models.

Rather than a designing a predictive model that attempts to emulate real world events, the study highlighted

the need for a low-cost informative model that can improve the understanding of Influence Operations amongst practitioners and their commanders.

3.0 SOLUTION

The “Influence and Infrastructure Combat Model” (IICM) is an agent based Human Terrain model intended to support military training and education requirements. Fundamentally, IICM is a novel wargames engine that allows the passage of sentiment to be modelled throughout a target population, both civil and military. Techniques have been adapted from existing social models by decreasing sensitivity to input data and adjusting the measurement of time to match the pace of kinetic events in a training scenario.

The project will run over 3 phases, each escalating the models Technology Readiness Level (TRL): -

- Phase 1 - Prototyping the Human Terrain model to prove its underlying concepts and to test its behaviour with reference to computational and source data requirements. (TRL 3/4). This phase concluded summer 2019.
- Phase 2 - Refinement of IICM to handle a contemporary, complex military scenario by linking the Human Terrain model into an existing Kinetic Warfare model. (TRL 4/5). This phase is due to begin late 2019.
- Phase 3 - Integration of IICM into a comprehensive Simulation and Modelling framework such as the UK proposed Synthetic Operating Environment. (TRL 6/7). This phase is expected in 2020-2021.

4.0 PROJECT METHODOLOGY

Phase 1 began by reviewing how other teams have addressed these topics. Notable research sources included: -

- Recent work by David Kilcullen (Out of the Mountains. ISBN-978-1849045117) and Stathis Kalyvas (The Logic of Violence. ISBN-978-0521670043) explored how social groups interact and compete, and how this links to contemporary Counter Insurgency doctrine. This topic was supported by concepts like Narrative Dominance, explored by other NATO working groups.
- Contemporary manual commercial wargames (notably GMT Games COIN series of wargames) demonstrated that a highly aggregated terrain coupled with an area control mechanism can provide enough complexity to model complex political topics, and to challenge a prospective training audience.
- Urban characterisation studies provided a mechanism for modelling populated areas. This saw notable input from Allan W. Shearers work on the Archaria scenario and related PEMSII characterisation work for NATO ACT.
- Infectious Disease modelling techniques explored the use of computational methods of simulating human interactions. These studies highlighted the importance of age in determining the frequency and scope of social interactions. They also introduced the concept of Compartment Models, a process by which the population is divided into compartments, with the assumption that every individual in the same compartment has the same characteristics.

This was followed by an investigation into potential datasets that could support the model. Since data acquisition costs are a major factor in training exercises, Open Source data was prioritised in this investigation. A promising source of social behaviour data was found in medical datasets which described social contacts between different age and cultural groups (for instance; Mossong J, Hens N, Jit M, Beutels P,

Auranen K, Mikolajczyk R, et al. (2008) Social Contacts and Mixing Patterns Relevant to the Spread of Infectious Diseases. PLoS Med 5(3): e74. <https://doi.org/10.1371/journal.pmed.0050074> .)

Following the review, a designed a systems architecture was designed which split the solution into four main building blocks based upon the critical capabilities we wanted to demonstrate.

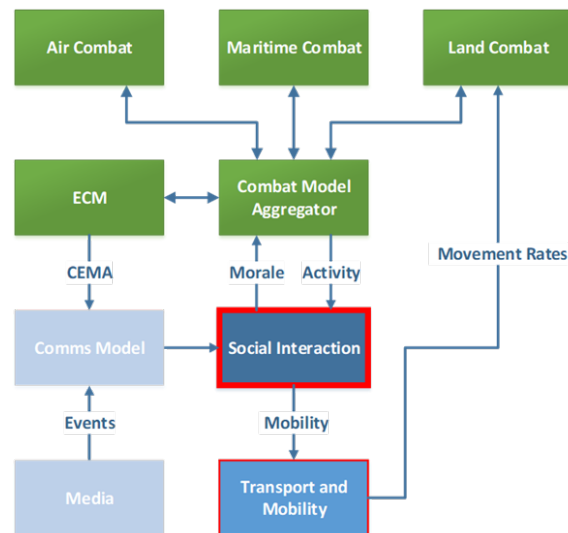


Figure 1: IICM Model Elements.

- Military activity affects the population. The “*Combat Model Aggregator*” acts a bridge into legacy kinetic models.
- Cyber and CNI disruption change electronic communications. A “*Capacity based Comms model*” models electronic information flow.
- People move over a daily cycle between different geographic areas. An Arc-Node based “*Transport and Mobility model*” allows population transport flows to be modelled and disrupted by external events.
- Information flows through a population. An “*Agent based Social Interaction model*” models the transmission of influence between people.

Elements of this design were prototyped to demonstrate the technical viability of the solution and to ensure that it was practical for use on a training event. The ‘Agent based Social Interaction Model’ and its associated ‘Transport and Mobility Model’ were prioritised for further investigation.

5.0 MODEL DESIGN

IICM models the Human Terrain through five different, interlinked concepts.

5.1 Geography

Geographically the exercise area is split into a small number of regions. Regions are selected to highlight major population features and include constraints on population mobility. Investigation showed that the

administrative regions used for census data often reflect underlying characteristics of the population behaviour.

Where practical, rural and urban areas are separated into different regions, highlighting the different patterns of behaviour exhibited by the population at a local level. Key infrastructure features such as communications hubs, transport nodes and major utilities have physical locations within these regions and act to transport resources between regions. A typical C2 training exercise requires 6 – 12 regions whilst analytical scenarios may use up to 20 regions.

5.2 Political

Politically, the Human Terrain is split into a relatively small number of competing factions. Factions can be used to represent political affiliations, tribal membership or other grouping which the training audience wish to measure or influence. The population is divided into Factions through Group Dynamics principles, using the concept of a 'Category' collection (that is a group that a person self-identified with). Remaining Group Dynamics collections (Primary, Social and Collective groups) are represented by other attributes in the model.

Competing military forces are included as active factions within the system. This allows their physical presence to generate influence on the wider population and permits them to be targeted by hostile influence operations.

Basic scenarios use at least 5 factions, typically including two or more military forces, the local government and at least two civil groups. Advanced scenarios require 10 or more factions, allowing greater fidelity of the civil population behaviour.

5.3 Population

IICM divides a regional population into small collections of people that share characteristics, called Population Groups (PG). Members of a PG share a common faction, age band, home region and work region and are assumed to be in a state of near constant communication amongst themselves. Consequently, IICM can use Group Dynamics principles to aggregate the behaviour of the PG members together to give a common response to external stimuli.

The model treats each PG as a semi-autonomous software agent and tracks them as they move between the different geographic regions and interact with each other. A typical scenario includes 100's to 1000's of these groups, each representing 25 – 1000 individuals.

5.4 Cultural Distance

Differences in cultural behaviour and language act as an impediment to successful communication between groups of people. IICM uses the concept of Cultural Distance (CD) to describe the ability of factions to communicate with, and so influence, each other.

Currently, IICM use a Lewis model to generate a single CD value that determines the chance of successful communication, irrespective of the communication channel. Enhanced versions of IICM will use a Hofstede Cultural Dimensions model to better reflect how each faction is perceived (and trusted) by other factions depending on the form which communication takes place, allowing better representation of mass media and social media.

5.5 Messages

IICM implements a SMCR communications model which describes information flow in terms of a Source, Message (Payload), Channel (Delivery Mechanism) and Receiver. The Source and Receiver are the PG entities communicating with each other. The message encodes a change of support (positive or negative) for a faction modelled in the system and includes information on the authors faction. Since IICM assumes that Face-to-Face communication is the most effective method of conveying complex information, this as the primary information channel.

A message can be described as an infectious agent (or Meme) which is passed between PG entities. Consequently, the behaviour of a message can be modelled using epidemiological Compartment Models. In common with biological systems, messages have the following key behaviours: -

- A message is normally transmitted when two PG's are in the same region and interacting with each other. The chance of interaction depends on age and other cultural factors.
- Some messages are more 'infectious' (believable) than others. The smaller the Cultural Distance between the message author and the recipient, the more chance of it changing the perception of the recipient.
- Messages can be 'misunderstood' as they are passed between PG's and so 'mutate' into a new form. The greater the Cultural Distance, the higher the chance of mutation.
- Some messages are more interesting than others and so have a higher 'virulence'. This allows them to take precedence during communications and so be exchanged faster throughout a population.
- Messages have a lifespan after which the information it encodes becomes 'stale' and no longer newsworthy. Once a message reaches this point it is no longer infectious and becomes dormant.

To represent the effects of social media and other background communications, IICM includes a smoothing model which allows influence scores (but not the underlying messages) to propagate throughout all members of a faction, no matter where they are physically located.

Message transmission and effects are evaluated on an hourly basis and results typically generated every 12 to 24 hours of exercise time to match a formations battle rhythm. Outputs take the form of graphs and bar charts showing the change of influence over time.

6.0 PROGRESS AND CONCLUSIONS

IICM is currently under active development. Key elements of the computer simulation have been designed, constructed and tested. Datasets representing a wide range of real world and fictional scenarios have been built using a combination of open source and synthetic datasets. These have been tested against the requirements of different user communities, including use on real training events.

Access to open source social contact models allowed the construction of viable training scenarios without resorting to Social Media derived datasets. However, this required an understanding of a local transport network and the location of key social gathering points like local markets and schools. The division of a population into age bands as well as political affiliations was essential to replicating real world test cases.

In its current form, IICM is best suited at describing human populations numbering 10,000 – 100,000 people. This covers the intended Battalion to Brigade mission sets and allows up to 10 days of activity to be modelled. The main limitation in exercise complexity is not computer processing power, rather the ability to present the resulting data in a format that can rapidly assimilated.

The next stage of development, Phase 2, will expand the communication model to include broadcast media and other electronic methods of communication. This will allow the flow of influence through a population to be altered by disruption to the communications chain, in turn allowing aspects of Cyber Warfare to be modelled. Refinements to the Combat Model Aggregator will allow the automatic generation of messages (and so influence) in response to activity within the kinetic warfare models. Enhanced methods of data presentation will also be trialled.



Simulating the Future Operating Environment for Training and Education

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ABSTRACT

Military operations are performed in an increasingly complex world where the behaviour of force elements is affected by the state of the natural environment, political effects and social effects, in addition to physical (kinetic) warfare effects.

Modelling and Simulation (M&S) systems have a limited representation of these aspects, and mainly provide static representations of the natural environment and physical warfare effects. The effects of electronic and information warfare such as offensive and defensive cyber and the use of social media as an influence tool are of increasing importance to military users. Current synthetic based training systems employ a component known as Computer Generated Forces (CGFs) to represent the majority of human and systems behaviour as an integral element of the simulation and/or Synthetic Environment (SE) used to deliver the training. However, no single CGF adequately represents the breadth of system, human, organisational and social behaviours that occur in operational environments, and often more than one CGF needs to be employed which were not designed to be interoperable which impacts the ability to provide consistent representation of effects across dissimilar simulation systems. This is a capability gap identified by previous research carried out by the UK Defence Science and Technology Laboratory (Dstl) in partnership with supplier organisations. Related to this issue, “Simulating Future Battlespace Complexity” is one of five UK Defence Innovation Priorities published by the UK MOD.

This paper describes research conducted by the UK Defence Science and Technology Laboratory (Dstl) into the representation of Future Operational Environments (FOE) in Simulation (FOESim). This is aimed at investigating methods and technologies relevant to representing the increasing complexities of operational environments in simulation in a more coherent and effective manner. The scope of this research includes,

- assessing opportunities for M&S to provide more efficient and effective training in Future Operating Environments (FOE);*
- new approaches for the composition of more coherent and improved representation of human and systems behaviour across simulation systems;*
- the representation of warfare effects on current and emerging operating domains such as space and cyber, including non-physical force behaviours such as electronic and information warfare effects;*
- consistent representation of dynamic natural effects such as weather and terrain on operational environments;*

ABOUT THE AUTHORS

Matthew Smith is an analyst at the UK Defence Science and Technology Laboratory (Dstl) in Training and Transformative Technologies Team. He graduated with a first class BSc (hons) in Games Design in 2015 where he specialised in virtual training simulation and realism. His current work focuses on the representation of the future operating environment for simulation (FOESim) and the exploitation of games development software for simulation as part of Dstl's Transforming Training, Education, and Preparation Project.

Neil Smith is a principal analyst at the UK Defence Science and Technology Laboratory (Dstl). He has over 45 years' experience in real-time simulation research activities, including the use of federated (distributed simulation) systems for defence training, mission planning/preparation, concept development and experimentation, support to defence acquisition programmes, test and evaluation. He is currently working as the Technical Lead for research into the representation of the Future Operating Environment in Simulation (FOESim) which is part of Dstl's Transforming Training, Education, and Preparation Project. This work is investigating processes and technologies aimed at achieving greater coherence and improved representation of operational environments and effects across defence synthetic based training systems.

1.0 INTRODUCTION

Military operations are performed in an increasingly complex and uncertain world where non-physical warfare effects such as cyber, electromagnetic and information warfare are playing greater roles in manipulating the battlespace in conjunction with current physical (kinetic) warfighting methods [1,2]. Simulation and Synthetic Environments (SSEs) have limited support for representing these effects which impacts defence capabilities in the use of synthetic based training systems. This was identified by previous research carried out by the UK Defence Science and Technology Laboratory (Dstl) in partnership with supplier organisations [3]. Furthermore, the UK Ministry of Defence (MOD) has identified the challenges of simulating the future battlespace complexity as one of top five innovation priorities for defence [4]. In doing so, UK MOD has recognised the need for more effective and efficient composable synthetic training environments.



Figure 1: Examples of Simulated Operating Environments and Effects

The employment of SSEs for defence applications including joint and combined (coalition) training and mission preparation will need to represent future operational environments in a more coherent and timely manner, to provide more efficient simulation delivery and support a wide range of effects in the operational space. As an example, Electronic Warfare (EW) and Information Warfare (IW), Cyber and the use of social media as an influence tool are becoming an important factor to defence operations and military decision makers. As IW becomes an increasingly central part of military operations, SSEs will need to evolve to represent it. However, the information environment and information effects are by their nature ambiguous and difficult to simulate, especially as they are driven by human behaviours and thought processes.

In order for military commanders to train in the future operating environment, it is important to provide evidence for the requirement to represent a wider spectrum of effects to meet challenge that will be presented by the future operating environment. This will include investigation into approaches for integrating emerging non-physical effects with physical force and natural environment effects as part of dynamic simulated environments within which forces can manoeuvre, implement, and respond to effects in operational environments.

This paper describes research being conducted by the UK Defence Science and Technology Laboratory (Dstl) into the representation of Future Operational Environments (FOE) in Simulation (FOESim) in a more effective and coherent manner. The research is investigating methods and technologies aimed at informing improved and more agile composition of SSEs beyond those currently being delivered which support a limited range of scripted effects of weather and physical (kinetic) warfare effects on operational behaviour.

This objective of this research is to benefit UK MOD by informing Policy and Strategy to achieve increased Force Readiness through the use of improved joint and combined (coalition) synthetic training systems which can be composed to represent the FOE in SSEs in a more timely, agile and consistent manner across defence.

Key recommendations and outputs from this research will consider how future SSE capabilities can be developed in accordance with the UK approach to Defence Modelling and Simulation Coherence (DMaSC¹). This includes the provision of common, shared enablers in order to maximise the utility of Modelling and Simulation (M&S) to enhance defence operational capabilities. The work will also consider the composition and deployment of SSEs in line with the NATO Modelling and Simulation as a Service (MSaaS) approach [5].

2.0 SCOPE OF RESEARCH

UK Defence Science and Technology (S&T) research over the next 3-4 years will include studies into the representation of FOE in Simulation. Specifically this will investigate methods and technologies to improve the simulation of people, institutions, and systems (and the collaborative and adversarial behaviours between them), in order to represent a wider spectrum of operational effects and the complexities of future environments in SSEs. This work is an element of the Dstl Transforming Training Education and Preparation (TTEP) Project that forms part of the Future Workforce and Human Performance (FWaHP) Research Programme.

Current synthetic based training systems do not support all of the factors that future decision makers will need to consider, including the effects that would result from these decisions, or complexities of these environments, i.e. the ‘5Cs’ described by the Defence Capability Development Centre (DCDC) [1].

- **Congested** – historically, in a conventional context, Defence Forces have usually sought to avoid a congested battlespace when trying to achieve freedom to manoeuvre.
- **Cluttered** – which leads to an inability to distinguish individuals, items or events, particularly in congested environments, provides the opportunity for concealment and will confound most Western sensors.
- **Contested** – adversaries will contest all environments where they seek to deny our freedom of manoeuvre.
- **Concealed** – military activities including both red and blue forces will continue to gravitate towards the inter-connected nodes.
- **Constrained** – in the complex battlespace of the future ‘Western’ legal and societal norms will place continued constraints on the conduct of operations.

Research already conducted has delivered two scoping studies [6,7,8,9] aimed at identifying areas of importance relevant to FOESim. These studies concluded that several key themes need further investigation. These include improving the representation, interaction and effects of human and autonomous systems behaviour, representing Hybrid Warfare behaviour such as cyber and social media effects, and the use of SSEs to represent complex urban environments for training.

Ongoing research into simulating the future battlespace includes two activity areas that will inform the development of more timely and coherent SSEs so that they can be composed and deployed in a more agile manner. This will contribute to increased ‘Force Readiness’, enabling the employment of new capabilities in simulation and will lead to a more efficient and effective use of simulation, including training for joint and combined (coalition) operations.

¹DMaSC provides a UK Defence wide coherent approach to provide better Modelling & Simulation (M&S) capabilities and reduced costs with less of an environmental impact.

- 1) People and Autonomous Systems – this activity is focussed on methods for improving the representation and composition of human and autonomous systems behaviours and the effects of operational environments on behaviour, e.g.
 - Composition and deployment of Computer Generated Forces (CGFs);
 - Improved scope and coherency of behaviour representation;
 - Operational effects and interactions between human and autonomous systems behaviours;
- 2) Future World – this research activity will include studies to address the representation of the future battlespace and emerging warfighting domains in simulation systems, e.g.
 - Representation of smart, large urban environments ('megacities'), including the complex physical, information and cognitive networks;
 - Simulation of emerging domains including Contested Electromagnetic Activities (CEMA), Information Warfare (IW), Cyber, and Space;
 - Consistent representation of the natural and physical environment including dynamic weather and terrain;
 - Development of Use Cases to inform a M&S approach to representing the future world;

2.1 Representation of Human and Autonomous Systems

2.1.1 Composition and Deployment of Behaviour

CGF constructive simulations are an integral element of synthetic based training systems used to represent the majority of behaviour. Given the challenges of sustaining through life support, traditional use of Government-Off-The-Shelf (GOTS) CGFs is being addressed through the increasing employment of Commercial-Off-The-Shelf (COTS) CGF systems. However, in many cases no single CGF adequately represents the breadth of platform, human, organisational, and social behaviours that occur in operational environments, which often results in more than one CGF is employed. Furthermore, the simulation of operational effects are often implemented in a pre-scripted manner in a given CGF, which affects the ability to provide consistent representation of effects across distributed simulation systems due to the bespoke representation of effects.

One of the longer-term visions of the Dstl research is to inform methods to develop a capability for composing and deploying a CGF either as a 'service' or integrated with a local simulation, based on a set of "disaggregated" behaviours. Figure 2 presents a roadmap for the evolution of this CGF deployment over the next 10 years, which also outlines two intermediary stages (i.e. "rationalise", "distil"). The objective is to provide a more agile mechanism for representing human behaviours, institutions, social systems and the increasing number of autonomous platforms that will require representation in future SSEs. Some of the activities currently being undertaken as part of NATO MSG [5] that aim to advance and promote the operational readiness of MSaaS are a key enabler for delivering this vision.

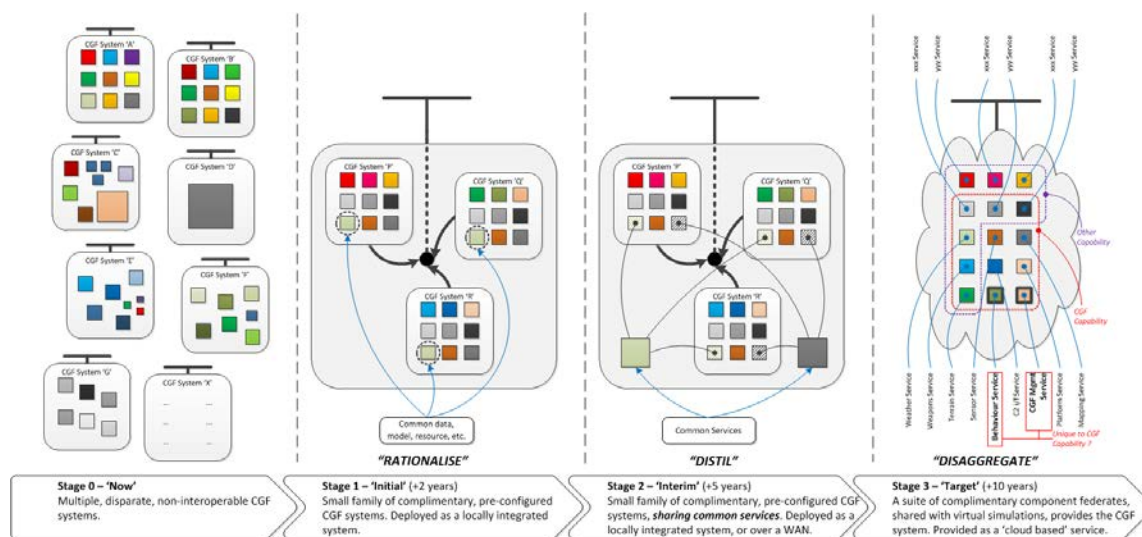


Figure 2: Example of a modular ‘composable’ CGF Architecture [10]

2.1.2 Consistent Representation of Human and Autonomous System Behaviour

Dstl research into the representation of Human and Autonomous Systems Behaviour (HASB) in a coherent manner across SSEs has continued to develop from previous research [11,12,13,14], in addition to work conducted by NATO MSG-127 [15], with a particular focus on operational and natural environment effects on human behaviour and autonomous systems.

Dstl commissioned two scoping studies [6, 9] to review and identify areas for further work relevant to the representation of HASB in simulation. The studies found that NATO MSG-127 research described many desirable aspects of a Human Behaviour Model (HBM), such as extensible design, standard compliance, and inclusion of a reference model, although did not attempt to define a realistic HBM. However, the scoping studies reported numerous gaps and challenges associated with representing HASB in simulations, including,

- a lack of consensus on the behavioural factors needed, and a similar lack of an agreed framework for their representation;
- a lack of available behavioural data sets to serve as a basis for building or validating HASB models;
- a lack of relevant technical standards or standards development activities;
- technical and architectural challenges associated with HASB simulation implementation;

As a starting point for developing a unified requirement for the representation of HASB in simulation, these studies have developed draft taxonomies of factors that affect HASB, based on integrating and rationalising factors found across multiple sources [8]. The taxonomies will serve as the basis for developing a common vocabulary and understanding across the disparate communities that need improved HASB simulation.

As part of the scoping studies into HASB in simulation, the work investigated the application of the draft taxonomies for use with a proposed Pattern of Life (PoL) Definition Language (PLDL) [16]. The PLDL is simulation agnostic and defines human behaviour independently of a geographical area with a current focus on representing ‘patterns of life’ within large-scale urban environments (“megacities”), using a Behaviour

Tree² approach. However, in trying to apply wider and more complex representations of behaviours, limitations to the Behaviour Tree method were realised. An extended version of Pattern of Life Definition Language (PLDL X) has been investigated which includes a wider range of behavioural factors and looks at other methods for authoring behaviour, including Utility Theory³, Steering Behaviours⁴ and Emotional State⁵ Representation, including a combination of these methods. These provide differing types of decision making, which allows modelling behaviour in detail and more accurately.

2.2 Representation of the Future World

2.2.1 Representation of Weather Effects

Representation of weather effects and climatic conditions within simulation systems has traditionally been poor, mainly due to lack of requirements and limitations in technology. This has resulted in disjointed approaches, which have typically resulted in,

- Two-dimensional representations of clouds for ground training systems, which cannot be re-used for airborne training systems;
- Atmospheric modelling which does not match reality; for example air temperature and pressure may affect a flight model but do not affect cloud formations;
- No link between representation of weather visually and its effect on the environment), systems, equipment and human behaviour;
- Disparities in weather representation within heterogeneous distributed simulation systems where some systems represent weather some do not, and some simulate contradicting weather;

Research has initially prototyped methods for representing coherent weather effects in simulation systems [17], engaging with the UK Meteorological Office for the provision of historical meteorological data. This explored ways of integrating and visualising consistent weather, including the effects of weather on systems and sensors. The UK Meteorological Office has a very extensive archive of Meteorological & Oceanographic (METOC) data, which provides a source of authoritative data to provide correlated representations of the state of the natural environment across SSEs.

² Behaviour Trees are a tree-based representation of hierarchical nodes that control the flow of decision making of an entity.

³ Utility Theory models behaviours by concurrently analysing many behaviour options and selecting a preferred one based on comparing a score (or ‘utility’) for each.

⁴ Steering Behaviours are based on a mathematical algorithm arising from vector addition, where one or more vectors represent a course of action that can be developed based on one individual factor (e.g. repulsion from an object or attraction to an object).

⁵ Emotional State is a behaviour authoring mechanism that allows entities to change and behaviourally ‘grow’ during a simulation scenario.

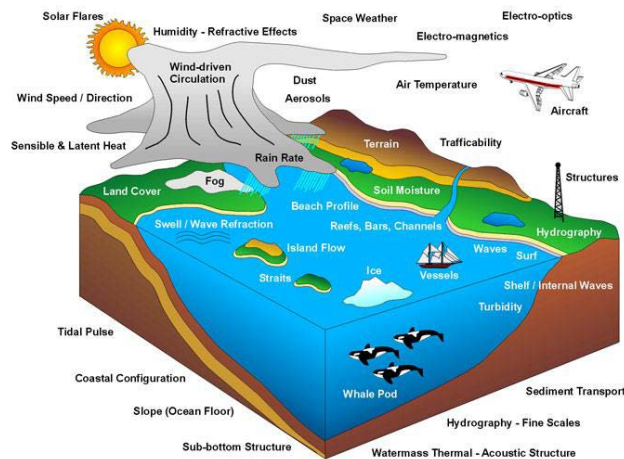


Figure 3: Example of Available Environmental Data

The representation of realistic weather and the effects of weather on operational environments is an important element of the use of SSEs for defence training. In most current simulations where the effects of weather are represented this is mainly static in both time and space, whereas real-world weather can be very dynamic and have significant effects on operational systems (e.g. effects of rain on sensors and ground vehicle mobility, atmospheric effects on unmanned air vehicles). Working in conjunction with coalition partners as part of the NATO MSG-156 Task Group (TG) on “Dynamic Synthetic Environments for Distributed Simulation” current research into methods for the representation of weather in SSEs is addressing,

- Which data sources are suitable to introduce realistic weather in SSEs?
- Methods and technologies to readily specify and integrate consistent weather data and its variations into distributed simulation systems.
- Which weather variations are important and need to be represented in SSEs.
- The representation of weather effects on natural terrain features, military platforms and systems in a consistent manner across SSEs.

2.2.2 Representation of Physical Force Effects

Research has demonstrated an approach to achieving consistent representation of terrain deformation across distributed simulations to represent the effects of a munitions explosion, such as damage to road networks and local infrastructure (see Figure 4). This was based on the use of the Open Geospatial Consortium (OGC) Best Practice of the Common Data Base Specification (CDB).



Figure 4: Deformed Terrain - Munitions Effects

CDB specifies an open format and encoding for the storage, access and modification of a representation of the natural and physical SNE for simulation applications. The CDB defines the data representation, organization and storage structure of a worldwide synthetic representation of the earth. This is assessed as a maturing technology that provides a level of flexibility for maintaining a repository of terrain source data, 3D model data [18].

When run-time modification of a terrain data set is required such as terrain deformation effects, a micro-service approach can be employed where the source data is modified with the modifications reflected through re-refinement of the repository source data. The research demonstrated a process for ‘down sampling’ terrain source data to reduce the Level of Detail (LoD) from a high resolution data set to LoD required by an end user simulation.

Data exchange between a storage repository and a simulation should use open standards, ideally such as those designed for the transmission of tiled geospatial data sets. Recommended standards are the OGC Web Map Service (WMS) and Web Coverage Service (WCS) interface standards for tiled raster data sets, and the Web Feature Service (WFS) for vector data sets.

The findings from this research are being used to contribute to NATO MSG-156 activities.

2.2.3 Representation of Non-Physical Force Effects

Non-physical force effects are the utilisation of methods that do not require the kinetic force. The development of hybrid warfare tactics that combine both physical and non-physical warfighting is becoming increasingly common, including the use of social media, which allows the analysis of social behaviour and provides readily available intelligence for control, manipulation, and targeting. One element of this is IW, which by its nature can be complex and subtle. Through analysis of previous research [19, 20] this raised the issue of modelling IW and the challenges that make it difficult to simulate. Previous research has investigated how the information domain could be described, which was intended to form the basis for an architecture around which subsequent experimentation could be conducted.

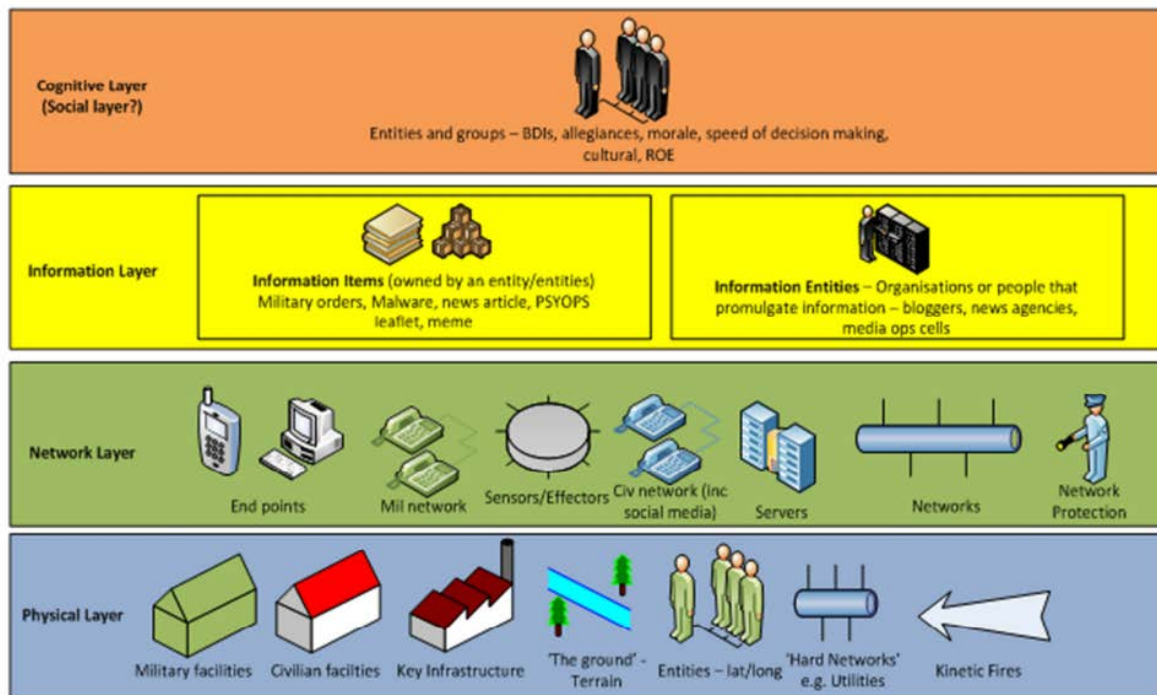


Figure 5: SCORE Development of TTCP JSA 2 KTA 3 Model

Several models were considered for representing the information domain in simulation including NATO Allied Joint Doctrine for Information Operations and The Technical Cooperation Program (TTCP) Joint Studies and Analysis (JSA) 2 Key Technical Area (KTA) 3. The Research Team developed the TTCP model further (see Figure 5) to represent to outline the component elements of each layer so that the information flow between the layers could be better understood. The model includes the following layers,

Physical Layer – Represents the location and state of physical infrastructure represented in the simulation, entities locations, and hardware such as communication towers. It also represents whether an entity has a means of communication in order to send a message i.e. they are next to or are carrying an operational communications device i.e. the battery is not flat. For people speaking to each other without the aid of any communication equipment, the network layer checks that they are physically close so could reasonably be expected to hear each other. In addition, the physical layer is required to represent physical weapon effects, for example is the communication infrastructure still operable after an attack.

Network Layer – Represents the ability to pass information between different network elements. Providing redundancy in the network enables messages to be received even if parts of it are disabled. The network layer will be affected by several effects including,

- destroying elements of the network infrastructure;
- electronic warfare e.g. jamming;
- line of sight e.g. between VHF transmitters/receivers;
- weather e.g. affecting atmospheric propagation of the electro-magnetic spectrum;
- cyber-attacks e.g. denial of service;

For some uses, it may only be necessary to represent the effect of the above on the network rather than having a detailed simulation. As an example, a denial of service attack could be represented by just disabling one of the nodes in a network.

The network layer should also control the propagation of the information on it, for example, representing the delays in receiving messages due to factors such as users not forwarding messages as a result of not immediately reading them or not having their phone with them.

Information Layer - Represents the information that is passed between entities or infrastructure on the physical layer in two forms. Control over the information layer should dictate the ability to change the content of the information, for example, if an aggressor obtains control of a communication system.

- Information Items – This is content that is owned by entities i.e. knowledge. This could take the form of orders, instructions or social media content.
- Information Entities – This organisations or people create or generate information content. Examples of this could include bloggers, news outlets, or military command and control elements.

Cognitive Layer - This layer represents the human element including allegiances, morale, and speed of decision-making. It can also identify groups/communities of users that are able to communicate with each other e.g. Skype address book. It provides the ability of introducing spoofing of users who can create fake news, etc.

3.0 PLANNED / FUTURE ACTIVITIES

3.1 People and Autonomous Systems

Based on outputs from the scoping studies, which includes taxonomies for representing human and autonomous systems behaviour, future work is planned to develop methods and reference architecture for reusable and composable behaviours in SSEs. The objective is to support a coherent ‘plug and play’ implementation, and to extend this to support to the behaviour of manned platform and remote controlled/autonomous systems. After an initial phase that will review definitions, roadmap and identify Use Cases, this work will focus on an experimental and exploitation phase, which will explore questions such as:

- Does the taxonomy of human and autonomous systems behaviour provide a foundation for composing behaviour as part of simulation systems?
- What is the future direction for methods and technologies for behaviour representation in simulation?
- What are the timescales for developing a suitable architecture for supporting a composite set of behaviours and their interactions in simulation systems?
- What simulation infrastructure is required? How are we going to test this infrastructure?
- What are the benefits/barriers to maximise wider defence exploitation?

3.2 Future Systems

A scoping study will be carried out to scope the performance, interactions, and effects of new and novel types of operational system capabilities that will need to be considered for representation as part of FOEs in SSEs. The aim of the scoping study is to,

- Investigate and review developments of future platforms (e.g. swarms of autonomous systems), weapons, and sensor technologies and their effects on future operating environments.
- Evaluate how these developments in defence systems will affect future synthetic training.
- Develop a Use Case that can be taken forward to evaluate the representation of future defence systems in simulation.

The findings from the scoping study will be used to inform the direction of future research relevant to providing advice and informing MOD on approaches for the simulation of the operational performance, interactions and effects of new and novel systems, e.g. sensors, weapons, platforms etc.

3.3 Representation of the Future World

Future research into PoL will look at demonstrating an enhanced representation of behaviour including disruptions to ‘patterns of life’ and infrastructure due a range of physical and non-physical effects. This will cover, but not be limited to, the effect of EW and IW effects such as offensive cyber, fake news and the effect of the destruction of infrastructure. In addition, the research will also investigate second and third order effects, for example the effect of damage to communications/utility networks, and manipulation of social media by hostile actors.

This work aims to demonstrate the ability to simulate the increasing complexities of future operating environments, including ‘megacities’ and emergent operating domains. Megacities are a complex geographical environment, which consist of congested spaces information networks used to manage smart environments. Furthermore, busy road networks limit the trafficability of land vehicles and tall skyscrapers make air support challenging if not impossible. There are challenges involved in representing such dense environments visually as well as being able to represent the effects on complex infrastructures such as transport and utilities.

Simulating human behaviour within megacities is a challenging problem. Much of the challenge is in addressing variations of scale; the megacity, by definition, must contain many thousands of human entities, but to be truly useful it must simulate each human’s behaviour at a high enough level of fidelity to produce realistic and believable patterns. Additional to this challenge is the technical and computational limitation of simulating such large numbers of entities in a high-fidelity virtual environment.

Games Engines⁶, such as Unreal Engine 4⁷, are looking to provide compatibility with technologies to support the representation of synthetic terrain formats such as the OGC CDB and simulation interoperability standards. Unreal 4’s ability to render larger entity counts, import complex urban environment models and deliver advanced physics models, could be utilised in conjunction with previous research and pattern of life to more accurately represent the second and third order effects of physical events in urban environments. The utilisation of games engine technologies will be reviewed as part of the Future World research.

4.0 RESEARCH OUTCOMES

The research outlined above is investigating the development of methods and technologies to provide coherent representation of the future operating environment in simulation for Training and Education (T&E), including the composition of people, institutions and autonomous systems behaviour. This will address a wider spectrum of operational effects and the complexities of these environments to support factors that future decision makers will need to consider in a complex and uncertain future world.

The output from this research aims to benefit UK MOD by informing Policy and Strategy relevant to supporting increased Force Readiness through an improved ability to represent the future operational environment in SSEs in a more timely and agile manner across Defence. The work will also position the external supplier base to develop simulation capabilities relevant to meeting future defence needs.

⁶ Games Engines are software development environments created primarily to develop Video Games. The environment provides existing high-end visual graphic rendering and physics and audio capability that provides a platform to develop. This provides significant advantages and greatly reduces development time and cost. Games Engines often provide access to a market place where third party add-ons can be purchased usually at no or relatively low cost which can further reduce development effort.

⁷ ‘Unreal 4’ is a games engine developed by Epic Games, which is predominantly developed for the Games Industry. Training and Simulation, of which a large part is defence, is considered to be one of Epics four market sectors alongside entertainment, architecture and automotive.

5.0 RECOMMENDATIONS

Related to this work there are several opportunities for collaboration with NATO MSG following on from the preliminary research studies including,

- The development and adoption of a common taxonomy and shared vocabulary for simulating HASB;
- recommendations for a future standard covering the utility of a simulation agnostic method for authoring PoL for use in simulation;
- A review of technologies, including gaming engines relevant to rendering larger entity counts, importing complex urban environment models and advanced physics based models for use in simulation;
- Simulation services to represent the FOE (megacities, behaviours, cyber, IW, EW etc.) that can be incorporated into an MSaaS architecture (MSG-164);⁴

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The Representation of Information Warfare effects in the Synthetic Battlespace

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ABSTRACT

The current generation of Simulations and Synthetic Environments (SEs) focus on physical warfare effects and do not adequately represent the wider spectrum of activities in the operational environment. In order to provide a more realistic environment, the next generation synthetic battlespace must include a better representation of other aspects of operations including information warfare, infrastructure, logistics, human interactions and the general populace.

Thales has led a project on behalf of the Defence Science and Technology Laboratory (Dstl) in the UK to research the provision of Information Warfare effects in the synthetic battlespace. This includes the ability to deny, degrade, corrupt or destroy the enemy's sources of information whilst preserving its own. The future synthetic battlespace must also enable synthetic entities to change their behaviour as a result of the information they receive through sources such as web sites, social media, television and radio.

To promote the reuse of Modelling and Simulation (M&S) across the defence community, the UK MOD has a desire to move away from monolithic simulations to more component architectures when representing the synthetic battlespace. In keeping with this approach, Thales has developed a 5 layer communications model in which the information can be manipulated at different stages of the communications chain.

1.0 INTRODUCTION

The aim of the UK Defence Science and Technology Laboratory's (Dstl) Simulation Composition and Representation of Natural and Physical Environments (SCORE) project was;

'To inform the development of coherent and consistent synthetic representations of the operating environment to provide more effective defence capabilities in support of training, concept development and experimentation, through-life acquisition and evaluation.'

The programme comprised a number of work packages that investigated the representation of weather effects and behaviours in simulation environments, and the reuse of simulation components. This paper describes the research Thales UK performed on investigating how information warfare effects can be introduced into simulation systems.

In the context of this paper, the word simulation is used to refer to a complex distributed simulation that is used to stimulate operational equipment.

1.1 Background

The current generation of distributed simulations focus on physical warfare effects and do not adequately represent the full gamut of activities in the operational space. In order to provide a more realistic environment, future simulations must include a better representation of other aspects of operations including human behaviour (e.g. sentiment, relationships, interactions), information warfare (e.g. cyber and psychological operations using social media, television/radio), infrastructure (e.g. electricity, gas, water, communication, food distribution, road and rail network), populace (e.g. number of people/vehicles, individual and group behaviours).



Figure 1 Capabilities Required in the Future Synthetic Battlespace

1.2 Information Warfare

In lieu of an agreed definition of Information warfare (IW), for the purposes of this paper, it is defined as ‘a concept involving the battlespace use and management of Information and Communication Technology (ICT) in pursuit of a competitive advantage over an opponent’ [1]. There are six aspects to Information Warfare;

- Physical information warfare – Denial of information to an adversary by physically destroying components of the information system;
- Electronic warfare - Denial of information to an adversary using electronic methods e.g. jamming;
- Psychological operations - Affect the state of mind of adversaries by using information against them;
- Military deception – Using information to make the adversary believe own capabilities and intent is far greater than they really are;
- Information attacks - Corrupt information without changing its original structure and location so that the recipient is unaware that it has been altered;
- Security measures - Prevention methods used in order to protect the information system so that it is not breached by an adversary.

Communication of information can be delivered by various means including visual, oral, and written and can be transmitted point-to-point or broadcast. However delivered, in the modern operational space, the propagation of information can be blocked, delayed or changed. This capability is used both by friendly forces and adversaries to influence the outcome of a campaign. It should be noted that the term information also includes the transmission of data i.e. information without context.

Future training systems must be able to represent all the different aspects of Information Warfare. However, there is a clear challenge in extending traditional approaches to simulation to satisfy these new requirements. Reference [2] describes the development of a conceptual model to support information and cyber warfare effects in modelling and simulation systems. The inclusion of Information Warfare effects needs to be seamlessly integrated with kinetic effects in future simulation environments.

A new ‘weapon’ available to both the military and adversaries is the use of Fake news, which is typically spread through broadcast systems such as TV, radio and web sites. The purpose of fake news is to surreptitiously alter the views of individuals, groups and the general populace. This can be used by the military to try and win-over the populace. Likewise it can be used by adversaries to turn the populace against say a peacekeeping force. As an example, misinformation about food handouts not complying with local religious practices could be generated to alienate a Peace Keeping Force from the local populace. Therefore, a commander needs to disrupt the flow of information and/or counteract it with messages that will neutralise the false messages.

1.3 Previous Research

Work within The ‘Technical Cooperation Program (TTCP) Joint Studies and Analysis (JSA) 2 Key Technical Area (KTA) 3’ proposed a layer based model for representing information warfare effects as shown in Figure 2 [3].

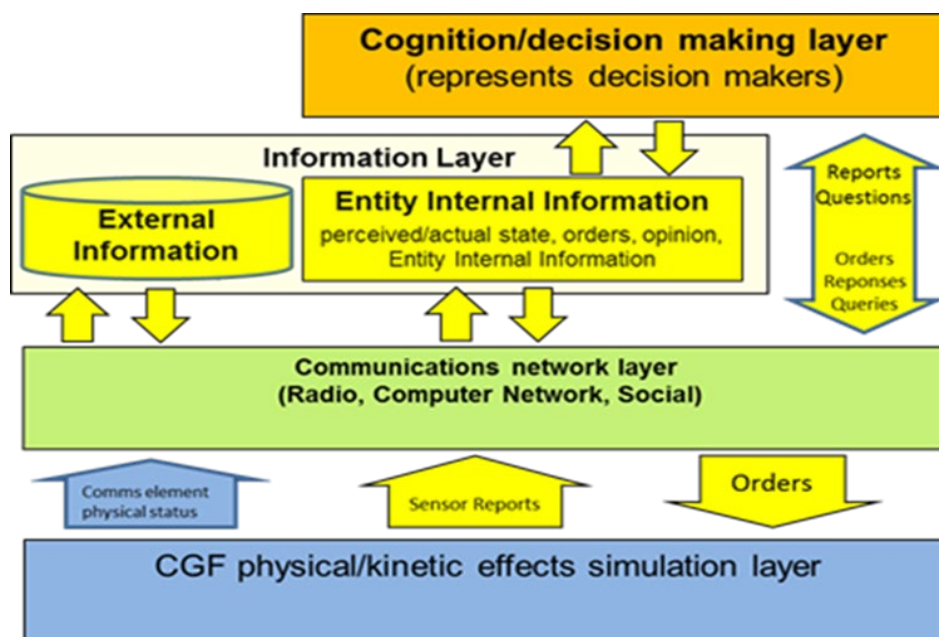


Figure 2 TTCP JSA2 KTA 3 Model

In the above model, there is a transition from physics-based to cognition-based processes (bottom to top). So the physics-based aspects of electronic attack and Cyber can be implemented in the Communications/

Networking layer, as would the removal of a key commander in a hierarchical command structure. The interception or modification of information content type of attacks would take place in the Information Layer, and finally, decision making processes are implemented in the top layer. Thus, EW and Cyber primary effects are applied at the middle two layers, but secondary and tertiary effects are driven by the modelling of the upper two layers and would manifest (be visualised) in the bottom layer as entity behaviour.

2.0 INFORMATION WARFARE IN THE SYNTHETIC BATTLESPACE

Whilst aspects of Information Warfare have been represented in simulators for a long time e.g. jamming communications, the current representation of communication systems is not sufficient to satisfy the latest needs. As an example, the use of more sophisticated representations of information systems is particularly required in large collective exercises where a commander and their team are being trained in a representative HQ (Figure 3).

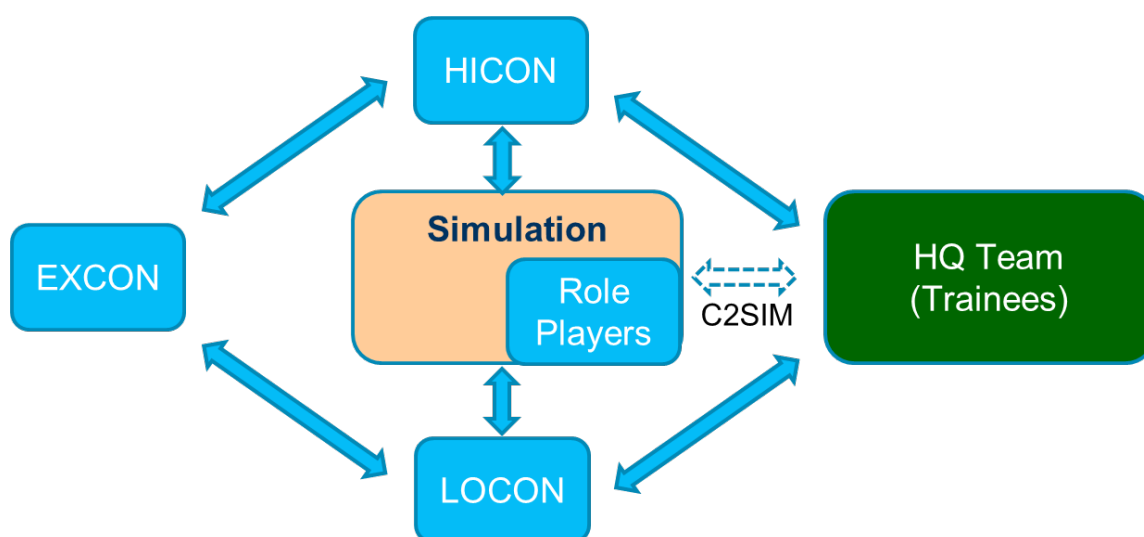


Figure 3 Elements of a Representative Exercise

In Figure 3, the simulation could be a large monolithic application or a complex distributed set of simulators and simulations. The ideal situation is where the HQ team use their normal operational C2 systems that are stimulated directly by the simulation using protocols such as C2SIM [4]. Currently the translation between the operational equipment and the simulation is mostly performed manually by the LOCON and HICON.

The EXCON is responsible for ensuring the training objectives are satisfied and for ensuring events from the Master Events List (MEL) are injected at the appropriate time. Depending on how well the HQ team are performing, the EXCON may also scale back or increase the complexity of the situation the commander has to deal with. The injects are passed to the LOCON who make the appropriate changes to the simulation e.g. evacuation helicopter crashes. The LOCON will also pass information from the simulation to the C2 systems in the HQ. The role of the HICON is to make decisions regarding the upper echelons in the chain of command. The HQ commander will report to them and they will feed back orders based on the political and strategic landscape. It should be noted that as well as a commander trying to disrupt information flow amongst adversaries, the effect of adversaries disrupting the information flows coming from and being sent to the HQ can also be disrupted.

From an information warfare perspective, the lines of communications that need to be represented in a simulation include those between:

- HQ commander and upper/lower echelons in the chain of command;
- Platforms e.g. Link16;
- Individuals e.g. military personnel, insurgents and civilians;
- Groups of people e.g. military personnel, insurgents and civilians;
- General populace.

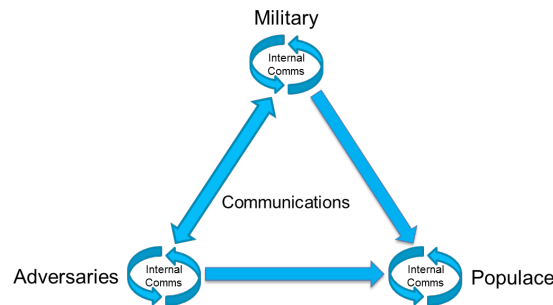


Figure 4 Lines of Communication

Information is transmitted using different media and the simulation environment should be able to disrupt the flow of information no matter how it is transmitted including:

- E-mails
- Texts
- Mobile phone / Telephone
- Personal radio
- Web sites
- Social Media e.g. Facebook, Twitter, LinkedIn
- TV / Radio

Commanders need training to understand what tools and techniques they have available to disrupt information flow between adversaries or even the population. In addition, they need to understand the importance of protecting studios for broadcast systems such as TV and radio to ensure that they are not overrun by adversaries who could send out their own messages. Where adversaries have the capability for sending out broadcast messages the commander needs to use their ability to jam the signals. Web sites providing official information need to be properly protected against cyber-attacks. Conversely, web sites promoting anti-government information need taking down.

3.0 5 LAYER COMMUNICATIONS MODEL

Figure 5 shows a logical mapping of different aspects of the battlespace onto 3 orthogonal domains.

Environment Domain – Represents the physical location and state e.g. operating/destroyed, of entities (platform and people) and infrastructure e.g. communication network, in the real and synthetic environment.

Cognitive Domain – Decision making by EXCON, exercise participants, role players either by real people or using Artificial Intelligence (AI);

Information Domain – Information flow through communication system;

The Representation of Information Warfare effects in the Synthetic Battlespace

A key facet of the model is that the inclusion of an information warfare capability doesn't disrupt the way existing '2 dimensional' simulations currently operate.

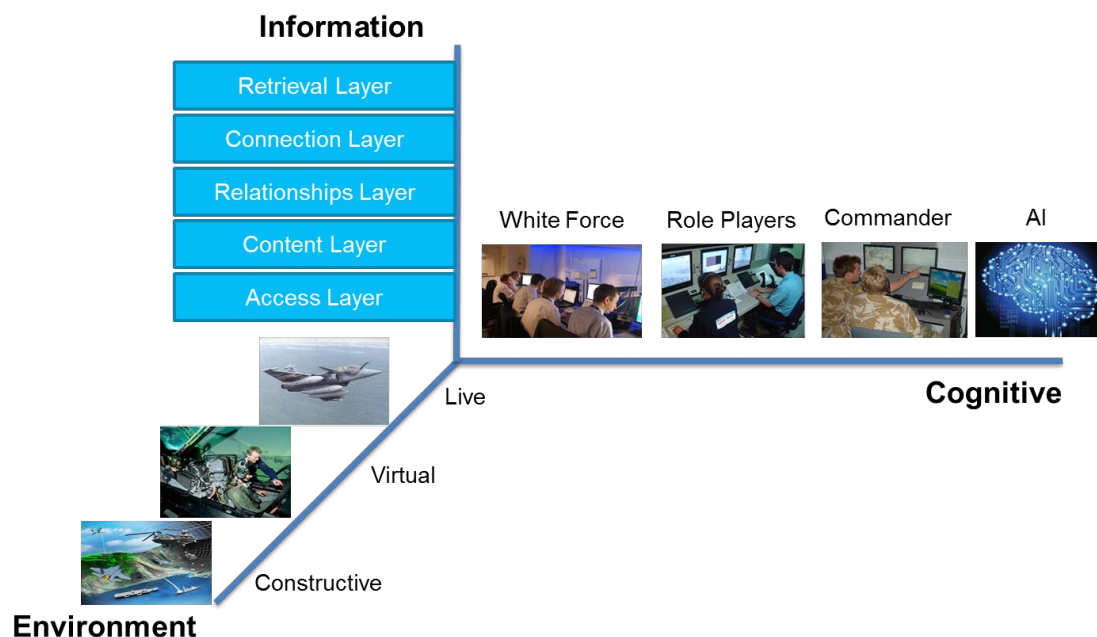


Figure 5 3 Axis Battlespace Model

The Environment domain includes operational C2 equipment and any physical infrastructure used by an exercise. The synthetic environment provides a wrapper to extend the physical environment of the HQ and represents all entities and infrastructure in the battlespace. Sensors in the synthetic environment typically stimulate the operational equipment used by the war fighters in the HQ. With respect to information warfare, the environment layer is responsible for representing the physical elements of the communication systems. These include the laydown of the communication bearers in the terrain e.g. copper or optical fibre cabling, intermediate network elements such as communication towers and the physical location of operator terminals. The Environment domain provides the means for disrupting communications using kinetic effects e.g. ordnance falling or being planted close to communication equipment that will render it inoperable. It also determines if a person represented by a CGF has an appropriate device for sending a communication e.g. are they carrying a mobile phone.

The Cognitive domain is where information from the Environment and Information domains is received and where decisions are made. These are made by commanders in the HQ who are endeavouring to accomplish the goals of the exercise. The EXCON may decide to introduce effects to challenge the commander and role players will make decisions to achieve the objectives they have been given. To reduce the number of white force players (i.e. all those supporting an exercise), which can be very costly, the use of more advanced AI techniques is being exploited in simulation environments.

The Information domain takes into account and isolates the factors that can disrupt the flow of information in the operational space. It is applicable to messages sent by any real or constructive people participating in or supporting an exercise and all the different forms of communication media.

The 5 Layer Logical Communication model is part of the Information Domain. The model was originally developed by SCORE [5] and has been further adapted as a result of writing this paper. It effectively

provides a generic approach to representing the functionality of the ‘Information Layer’ described in [3].

The following provides a brief description of the information layers, which are described in more detail in the following sections.

Access Layer – Determines if people have access to a communication device;

Content Layer – Provides the ability for the message’s recipient or sender to be changed, or for the content of the message to be altered;

Relationships Layer – Identifies groups/communities of users that are able to communicate with each other e.g. Skype address book;

Connection Layer – Determines if there is a path through the communication network between the sender and recipient of a communication;

Retrieval Layer – Represents the delays associated with when a message is accessed and acted upon.

A prerequisite for a person to be able to send or receive a message is that they must have access to either physical or simulated communication equipment, which would be represented in the Environment Layer. Information flows from the sender’s communication equipment through to the Connection Layer and then to the receiver’s communications device also represented in the Environment Layer.

In order for a person to successfully receive a message over a communication network, the following conditions must be satisfied:

- Access Layer - Sender/receiver must be physically close to or holding the communications device being used;
- Content Layer: Message ‘header’ or content must not have changed;
- Relationships Layer: The receiver must be in the same user group as the sender;
- Connection Layer: At least one communication path must exist between the sender/receiver;
- Retrieval Layer: Receiver must look at communications device.

It should be noted that as a logical model there may not be a one-to-one mapping between each layer and a service that provides the desired functionality. In some instances a single tool may be sufficient to represent the effects of all the layers.

3.1 Access Layer

The Access Layer determines that when a person wants to communicate with somebody else, both sender and receiver have access to a suitable communication device. This can be achieved automatically by interrogating the Environment to determine the location of the communication equipment and people using it. The output from the Access Layer service is True /False corresponding to whether the communication can occur or not.

3.2 Content Layer

The purpose of the Content Layer is twofold; to provide the ability for the name of the recipient or sender to be changed and to change the content of a message without the sender or receiver necessarily knowing what has happened. This enables the effects of spoofing to be simulated, which is the forgery of an email header so that the message appears to have originated from a legitimate sender rather than the actual

fraudulent source. Information about people such as mobile numbers for texting, e-mail addresses, social media usernames and passwords is commonly obtained using social engineering tactics. E-mail spoofing is a popular tactic used in phishing and spam campaigns because people are more likely to open a communication when they think it has been sent by a legitimate or familiar source. The goal of email spoofing is to get recipients to open, and possibly even respond to, a solicitation [6]. A spoofed email may also include a link that installs malware on the recipient's device if clicked.

The Content Layer also enables the content of the message or web site to be corrupted by simulating attacks on the communication system. Making parts of the message unreadable could lead to misinterpretation of the message resulting in commanders making incorrect decisions. If the communication system is compromised by an adversary, the tactic of subtly changing the content of the message may be used to tarnish the image of the impersonated sender e.g. peace keeping force. This capability could be used to alter the mood of enhanced behaviour models.

A simple Content Layer service would store a message in a queue to be manually processed and forwarded by the HICON or LOCON. This will enable them to change the message header or content so they are commensurate with the objectives of the exercise. The use of AI techniques to understand the message content may in future provide some form of automatic or at least semi-automatic way of changing the content of the message. The fidelity of the spoofing attacks to be simulated will be dependent on the objective and scale of the exercise being performed. However, it is conjectured that in most situations it will not be necessary to actually represent the content of the message but only its effect.

3.3 Relationship Layer

The Relationship Layer defines which people are able to communicate with each other. For text messages and e-mails it would define who is in their list of contacts. For social media it would specify what groups they are associated with. This function influences how messages are spread throughout the populace when sent to many people in an address book.

The input to a Relationship Layer service could simply access a spreadsheet that contains the names of the key players in the exercise, who is in their contact list and what groups they belong to. A more sophisticated implementation could implement it as a relational database. When a message is received, the Relationship service would check the message header to see if the sender and receiver are known to each other. If not, the message is discarded and not passed onto the Connection Layer.

3.4 Connection Layer

The Connection Layer controls the ability to transmit a message as a result of the interconnections and operational state of components in a communication network. This includes the communication bearers e.g. copper cables, optical fibre, and network components such as access points, switches and servers. Key components in the Connection Layer should have a corresponding representation in the Environment domain. This is to enable these components to be destroyed or disabled by activities that take place as the scenario unfolds.

Connectivity can be affected by several effects including:

- Loss of power;
- Elements of the network infrastructure being destroyed;
- Electronic warfare e.g. jamming;
- Loss of line of sight e.g. between VHF transmitters/receivers;

- Weather e.g. affecting atmospheric propagation of the electro-magnetic spectrum;
- Cyber-attacks e.g. denial of service.

The Connection Layer is initialised by storing the physical location of all the network elements being modelled and key personnel (constructive or role player) participating in the exercise. During an exercise, it receives the status of the communication equipment i.e. operating/destroyed from the Environment domain. It also receives the updates to the location of mobile communication devices and that of key personnel. This is important as it is used to determine whether a person has the means and is able to communicate with somebody else in the exercise. This could be due to being out of range or not having line of sight to a communications tower, or they are not next to or are carrying a communications device. For people speaking to each other without the aid of any communication equipment, the connection layer determines if they are physically close so could reasonably be expected to talk to each other.

COTS and open source network emulators are currently available that provide the required functionality for representing communication networks. These can be interrogated by a Connection Layer service to determine if there is connectivity between two communication devices. In order to degrade the transmission of a communication signal due to low bandwidth or jitter, the output from operational equipment can be passed through a network emulator.

Communication systems can be very complex with redundant paths and elements to provide resilience. However, it should always be borne in mind that the simulation should not be more complex than is needed to represent the desired effect. For some exercises, a realistic simulation of the key components in a network may be required to represent the effect of a denial of service attack overloading a server. In other exercises it may only be necessary for the EXCON to inject an event stating that a cyber-attack has taken place and that no messages will be transmitted through the Connection Layer.

3.5 Retrieval Layer

The Retrieval Layer simulates the real world latencies related to when people receive and process messages. With respect to receiving text messages on mobile phones, this could be because someone has their phone on 'Do Not Disturb' or they just miss the notification. When messages are propagated by social media e.g. Facebook, it can represent the delay in reading and forwarding messages. For information spread via web sites, the latencies relate to how often people would look at a particular page. For broadcast messages, it corresponds to whether someone or a group of people is watching or listening to the TV or radio (in this case, the message would either be received or not received).

The requirement of a Retrieval Layer service would be able to control the delay before the message can be accessed by the communication device. The delay could be produced using a random number generator that is initialised to control a delay profile for each participant and/or message.

4.0 SCORE EXPERIMENTATION

SCORE experimented with how existing and new services could be combined to represent Information Warfare effects in a simulation.

4.1 Degradation of Communications Using Real Equipment

To demonstrate how the performance of real operational equipment can be degraded in an exercise the communication path for a Skype call was routed through a network emulator. The network emulator provides the ability to degrade the signal by altering the amount of jitter and latency experienced by the transmitted data. This manifested itself as a poor quality video and voice, which made it harder to

communicate. The communication link was finally lost when the latency was too great.

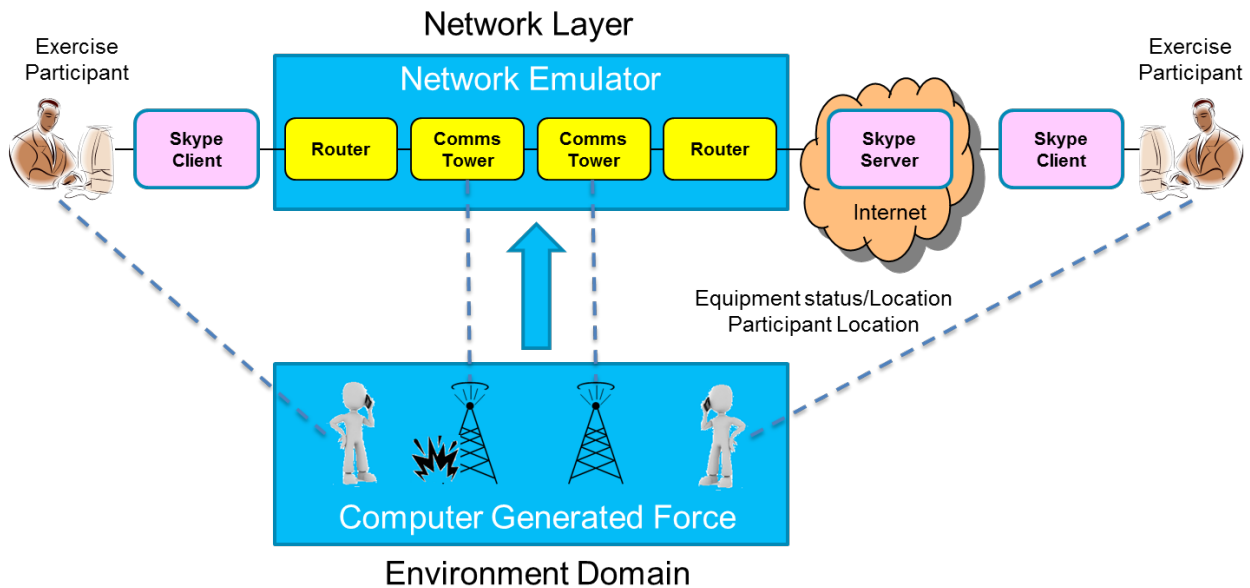


Figure 6 Degradation of Communications Using Real Equipment

The network emulator had an Application Programming Interface (API) that enabled the attributes of communication elements being modelled to be controlled programmatically. This ability was used to control the status of a communications tower and to change the location of the sender and receiver. As the sender and receiver moved out of range of the communications tower, as determined by the CGF, the Skype signal was lost. It was also lost when a kinetic effect represented by the CGF in the Environment domain caused one of the communications towers to be destroyed. In addition to video and voice calls, the approach is also applicable to sending e-mails and texts.

4.2 Message Propagation

The Message Propagation experimentation explored the use of a Connectivity service to determine connectivity between two entities by interrogating a network emulator (Figure 7). This was used to demonstrate the effect of a text message being propagated around a group of people. In this case the message is not actually sent through the network emulator but the ability to send message is indirectly affected as a result of there being a path between the sender and receiver or not.

During initialisation, the actual position of 3G/4G base stations in the area of interest, which was derived from government data, was downloaded to the network emulator. Entities were created in the network emulator to represent people in the scenario that had mobile phones and their location was updated in real-time by the CGF.

SCORE developed a Propagation service that could be configured to represent latencies related to when people would have read and forwarded a message. The Propagation Service provided the identity and location of the sender and receiver as inputs to the Connectivity Service. This interrogated the network emulator to determine if people represented in the CGF were within range of a 3G/4G base station to be able to receive or send messages.

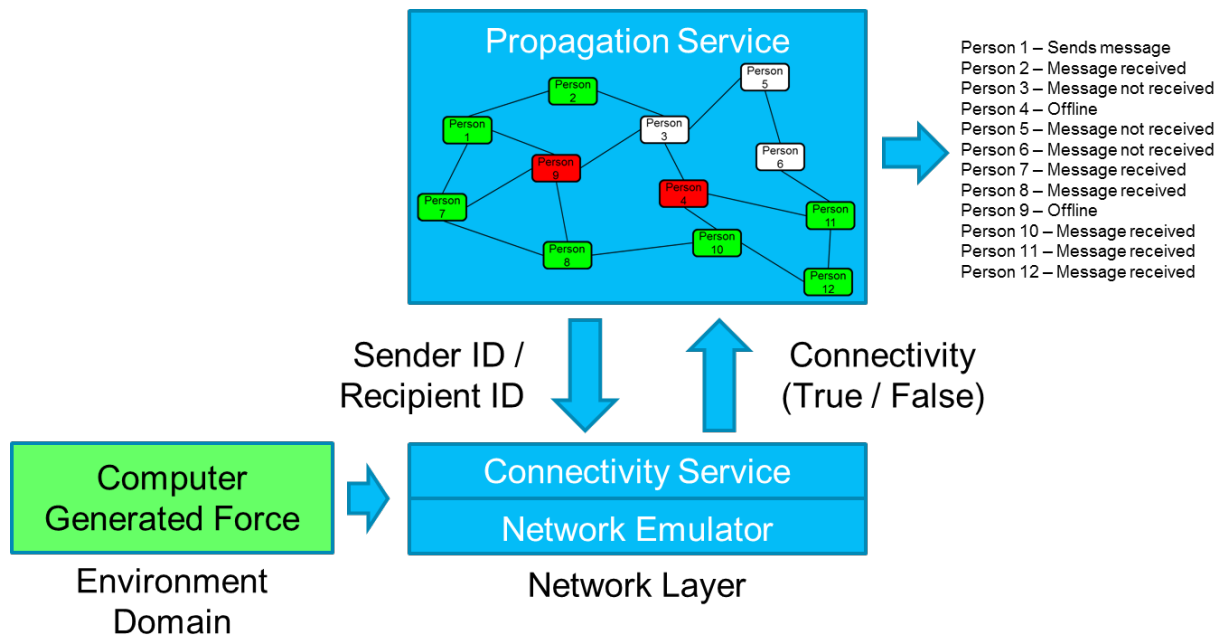


Figure 7 Demonstration of Message Propagation

The Propagation Service was initialised with random delays to represent when a person looked at a message and when they forwarded it. To demonstrate propagation delays, the Propagation Service displayed icons, representing the people in the scenario, which changed colour when messages were received. As people moved around they would come in and out of the range of the base stations and their icon turned red until connectivity was re-established and green when they received a message.

The Connectivity service was integrated with the CGF using the High-Level Architecture Evolved (HLA-E). By isolating the network emulator from the rest of the simulation, it has the advantage that if a different network emulator was used, it is only necessary to add another interface to the Connectivity service and it is not necessary to change the interfaces of other services that require access to it.

5.0 CONCLUSIONS

The current generation of Simulations and Synthetic Environments (SEs) focus on physical warfare effects and do not adequately represent the wider spectrum of activities in the operational environment. In order to provide a more realistic environment, the next generation synthetic battlespace must include a better representation of other aspects of operations including information warfare, infrastructure, logistics, human behaviours/interactions and the number of people represented in a simulation. The future synthetic battlespace must also enable synthetic entities to change their behaviour as a result of the information they receive through sources such as web sites, social media, television and radio.

The inclusion of information warfare effects greatly increases the realism for simulating the modern operational space as it can better represent the ‘fog-of-war’. In future simulations, when a commander sends an order, it cannot be assumed that the recipient will receive it immediately or at all. It might even be that the message itself has been interfered with. The inclusion of more representative communication models will increase the scope of training that can be performed. The SCORE experimentation showed that it is possible to provide an information warfare capability by integrating new capability to the existing approach to simulation, which enables it to be retrofitted to legacy simulations.

The 5 Layer Communication Model described in this paper extends the TTCP JSA2 KTA 3 model by providing a structured approach to degrading and corrupting communications. It is relevant to all types of communication media e.g. e-mails, texts, social media. Isolating the factors that affect the ability to transmit messages into these layers facilitates a more representative method of disrupting communications than can currently be represented in simulations. It also has the advantage that each factor can be changed independently and that the effect is automatically propagated to any other services that use communications. As an example, if a communications component e.g. communications tower, is immobilised by physical or cyber effects, it will not be possible for any communication devices using that network element to be able to pass messages (unless there are redundant paths).

The communications model is a logical model and that there does not have to be a one-to-one mapping between the different layers of the communications model and the services/applications providing the required functionality. For example, as some CGFs are now able to represent networks as well as entities such as people and platforms, the functionality provided by the CGF may span several layers. The provision of the functionality required by each layer of the communications model could be provided as a service, which is commensurate with NATO desire to provide Modelling & Simulation as a Service [8]. The services should have a user interface so that their effect can be manipulated during an exercise by the white force but more importantly, they should have an Application Programming Interface (API), to enable changes to be made programmatically.

The inclusion of information warfare in a simulation means that in future, scenarios will need to support additional data types e.g. for defining network topology. Further research is needed to identify the functionality required by services supporting the 5 Layer Communications Model, and to agree standards for exchanging information. Where possible, existing standards should be employed such as the use of Shape files for defining the physical routing of the network infrastructure and Digital Terrain Elevation Data (DTED) for defining the terrain. In future, network emulators need to be able to receive and respond to weather effects using the standards being defined by MSG-156.

There is an old adage that says ‘every model is wrong, but some are useful [7]. The art of simulation is just providing sufficient fidelity to satisfy the requirements without producing a ‘gold-plated’ solution. Whilst the need to be able to better represent information warfare effects in simulation environments has been recognised, the solutions employed can be very different. The criteria for what kind of solution is to be employed, is very dependent on the effect it must achieve. In some cases, it may be sufficient just to block a message getting through or it may only be necessary to simulate the effect of sending a message rather than its content e.g. it changes someone’s allegiance. If the timing of a message is important to an exercise then a more sophisticated simulation is required to represent latencies in the transmission and receipt of messages. Future systems for providing Information Warfare training should be able to represent all the tools available to a Commander and the effect of their actions or inaction; did it prevent or cause an attack taking place, has it reduced or increased tensions in the population did they target the correct person or group of people?

The SCORE experimentation demonstrated different solutions for implementing the 5 Layer Communication Model; communications could be degraded by passing information through a network emulator or its output used indirectly to affect communications. The approach to be used in an exercise is dependent on the type of communication being transmitted and the requirements for the simulation. SCORE demonstrated that by passing information through a network emulator, it is possible to degrade e-mail and text video/voice streams sent via operational equipment that is used in an exercise. This enables communications in the chain of command to be disrupted i.e. between a Commander and the HICON/LOCON, and between other participants in the exercise.

The inclusion of information warfare effects in a simulation will require more advanced behaviour models for constructive entities so that they can respond to the effect of the communications. These would be associated with the Cognitive domain. SCORE demonstrated the use of a ‘Disposition’ service that altered

the mood and allegiance of constructive entities depending on the information they received [5]. In the future, constructive entities rather than the LOCON should be able to automatically generate messages that create the background traffic that are used to mask important messages that a Commander should react to.

The SCORE experimentation has shown that the High-Level Architecture (HLA) and Distributed Interactive Simulation (DIS) are appropriate for communicating the location of entities from a CGF to a network emulator. The use of network emulators will provide a quick-win for representing the disruption of communications in simulations. It is recommended that new standards should first focus on producing a standard for initialising and controlling network emulators as there is a danger of a plethora of proprietary standards emerging for these tools. SCORE demonstrated the use of a network service that could be used to provide a common interface to different network emulators, which could provide an intermediate solution until standards become available.

As well as the network emulators representing communications networks, they could also be used in future to simulate utilities such as power distribution and water networks. Infrastructure such as electricity sub-stations and pumping stations could also be represented in the Environment Layer. The effect of these utilities not being available could be used to negatively affect the mood of the populace, which could change the outcome of an exercise.

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The Representation of Information Warfare effects in the Synthetic Battlespace

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ABSTRACT

The current generation of Simulations and Synthetic Environments (SEs) focus on physical warfare effects and do not adequately represent the wider spectrum of activities in the operational environment. In order to provide a more realistic environment, the next generation synthetic battlespace must include a better representation of other aspects of operations including information warfare, infrastructure, logistics, human interactions and the general populace.

Thales has led a project on behalf of the Defence Science and Technology Laboratory (Dstl) in the UK to research the provision of Information Warfare effects in the synthetic battlespace. This includes the ability to deny, degrade, corrupt or destroy the enemy's sources of information whilst preserving its own. The future synthetic battlespace must also enable synthetic entities to change their behaviour as a result of the information they receive through sources such as web sites, social media, television and radio.

To promote the reuse of Modelling and Simulation (M&S) across the defence community, the UK MOD has a desire to move away from monolithic simulations to more component architectures when representing the synthetic battlespace. In keeping with this approach, Thales has developed a 5 layer communications model in which the information can be manipulated at different stages of the communications chain.

1.0 INTRODUCTION

The aim of the UK Defence Science and Technology Laboratory's (Dstl) Simulation Composition and Representation of Natural and Physical Environments (SCORE) project was;

'To inform the development of coherent and consistent synthetic representations of the operating environment to provide more effective defence capabilities in support of training, concept development and experimentation, through-life acquisition and evaluation.'

The programme comprised a number of work packages that investigated the representation of weather effects and behaviours in simulation environments, and the reuse of simulation components. This paper describes the research Thales UK performed on investigating how information warfare effects can be introduced into simulation systems.

In the context of this paper, the word simulation is used to refer to a complex distributed simulation that is used to stimulate operational equipment.

1.1 Background

The current generation of distributed simulations focus on physical warfare effects and do not adequately represent the full gamut of activities in the operational space. In order to provide a more realistic environment, future simulations must include a better representation of other aspects of operations including human behaviour (e.g. sentiment, relationships, interactions), information warfare (e.g. cyber and psychological operations using social media, television/radio), infrastructure (e.g. electricity, gas, water, communication, food distribution, road and rail network), populace (e.g. number of people/vehicles, individual and group behaviours).



Figure 1 Capabilities Required in the Future Synthetic Battlespace

1.2 Information Warfare

In lieu of an agreed definition of Information warfare (IW), for the purposes of this paper, it is defined as ‘a concept involving the battlespace use and management of Information and Communication Technology (ICT) in pursuit of a competitive advantage over an opponent’ [1]. There are six aspects to Information Warfare;

- Physical information warfare – Denial of information to an adversary by physically destroying components of the information system;
- Electronic warfare - Denial of information to an adversary using electronic methods e.g. jamming;
- Psychological operations - Affect the state of mind of adversaries by using information against them;
- Military deception – Using information to make the adversary believe own capabilities and intent is far greater than they really are;
- Information attacks - Corrupt information without changing its original structure and location so that the recipient is unaware that it has been altered;
- Security measures - Prevention methods used in order to protect the information system so that it is not breached by an adversary.

Communication of information can be delivered by various means including visual, oral, and written and can be transmitted point-to-point or broadcast. However delivered, in the modern operational space, the propagation of information can be blocked, delayed or changed. This capability is used both by friendly forces and adversaries to influence the outcome of a campaign. It should be noted that the term information also includes the transmission of data i.e. information without context.

Future training systems must be able to represent all the different aspects of Information Warfare. However, there is a clear challenge in extending traditional approaches to simulation to satisfy these new requirements. Reference [2] describes the development of a conceptual model to support information and cyber warfare effects in modelling and simulation systems. The inclusion of Information Warfare effects needs to be seamlessly integrated with kinetic effects in future simulation environments.

A new ‘weapon’ available to both the military and adversaries is the use of Fake news, which is typically spread through broadcast systems such as TV, radio and web sites. The purpose of fake news is to surreptitiously alter the views of individuals, groups and the general populace. This can be used by the military to try and win-over the populace. Likewise it can be used by adversaries to turn the populace against say a peacekeeping force. As an example, misinformation about food handouts not complying with local religious practices could be generated to alienate a Peace Keeping Force from the local populace. Therefore, a commander needs to disrupt the flow of information and/or counteract it with messages that will neutralise the false messages.

1.3 Previous Research

Work within The ‘Technical Cooperation Program (TTCP) Joint Studies and Analysis (JSA) 2 Key Technical Area (KTA) 3’ proposed a layer based model for representing information warfare effects as shown in Figure 2 [3].

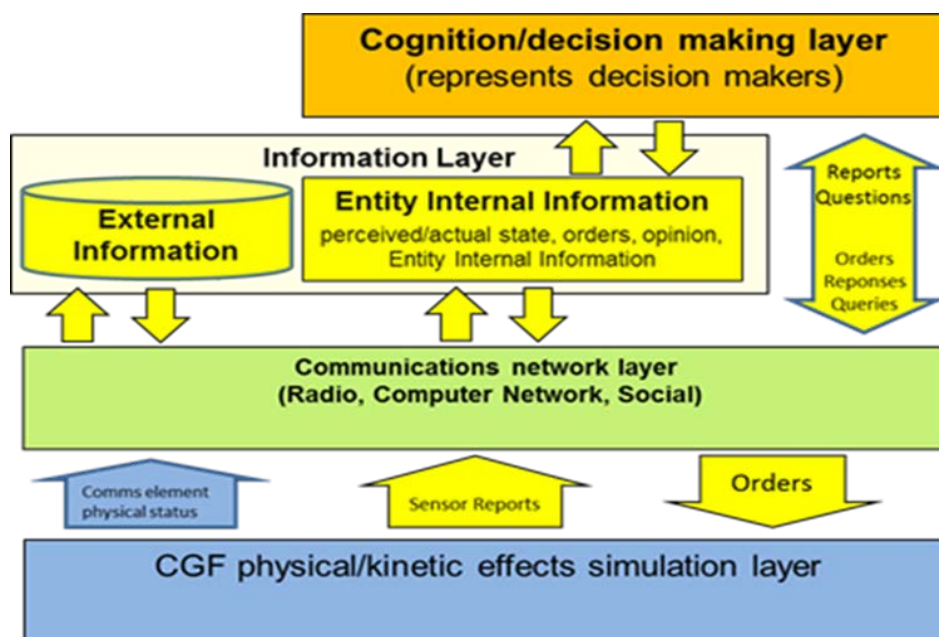


Figure 2 TTCP JSA2 KTA 3 Model

In the above model, there is a transition from physics-based to cognition-based processes (bottom to top). So the physics-based aspects of electronic attack and Cyber can be implemented in the Communications/

Networking layer, as would the removal of a key commander in a hierarchical command structure. The interception or modification of information content type of attacks would take place in the Information Layer, and finally, decision making processes are implemented in the top layer. Thus, EW and Cyber primary effects are applied at the middle two layers, but secondary and tertiary effects are driven by the modelling of the upper two layers and would manifest (be visualised) in the bottom layer as entity behaviour.

2.0 INFORMATION WARFARE IN THE SYNTHETIC BATTLESPACE

Whilst aspects of Information Warfare have been represented in simulators for a long time e.g. jamming communications, the current representation of communication systems is not sufficient to satisfy the latest needs. As an example, the use of more sophisticated representations of information systems is particularly required in large collective exercises where a commander and their team are being trained in a representative HQ (Figure 3).

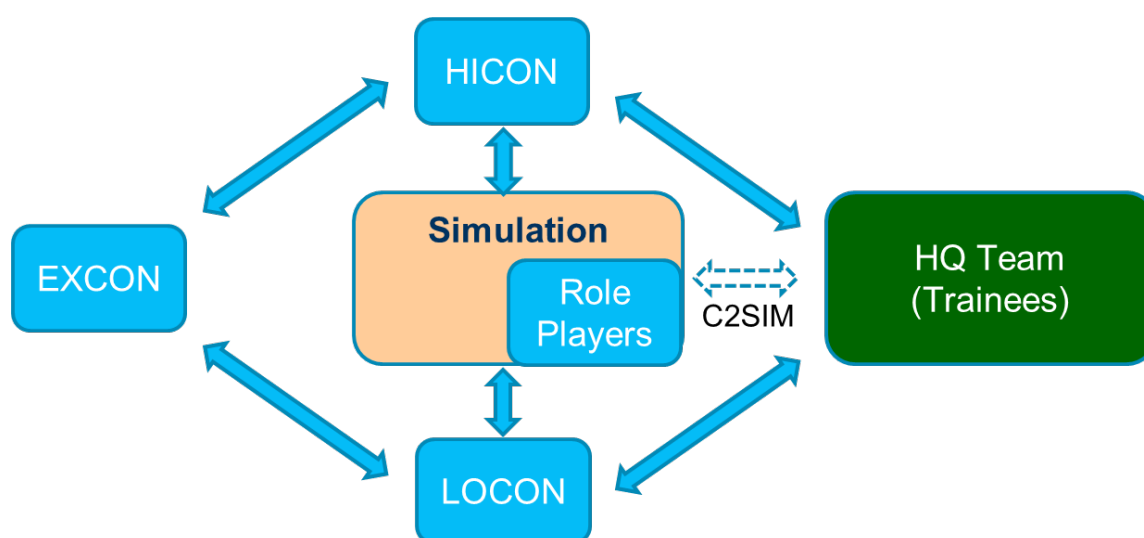


Figure 3 Elements of a Representative Exercise

In Figure 3, the simulation could be a large monolithic application or a complex distributed set of simulators and simulations. The ideal situation is where the HQ team use their normal operational C2 systems that are stimulated directly by the simulation using protocols such as C2SIM [4]. Currently the translation between the operational equipment and the simulation is mostly performed manually by the LOCON and HICON.

The EXCON is responsible for ensuring the training objectives are satisfied and for ensuring events from the Master Events List (MEL) are injected at the appropriate time. Depending on how well the HQ team are performing, the EXCON may also scale back or increase the complexity of the situation the commander has to deal with. The injects are passed to the LOCON who make the appropriate changes to the simulation e.g. evacuation helicopter crashes. The LOCON will also pass information from the simulation to the C2 systems in the HQ. The role of the HICON is to make decisions regarding the upper echelons in the chain of command. The HQ commander will report to them and they will feed back orders based on the political and strategic landscape. It should be noted that as well as a commander trying to disrupt information flow amongst adversaries, the effect of adversaries disrupting the information flows coming from and being sent to the HQ can also be disrupted.

From an information warfare perspective, the lines of communications that need to be represented in a simulation include those between:

- HQ commander and upper/lower echelons in the chain of command;
- Platforms e.g. Link16;
- Individuals e.g. military personnel, insurgents and civilians;
- Groups of people e.g. military personnel, insurgents and civilians;
- General populace.

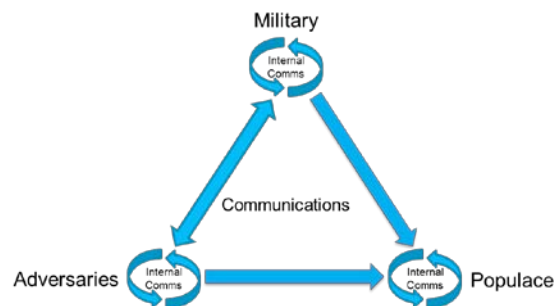


Figure 4 Lines of Communication

Information is transmitted using different media and the simulation environment should be able to disrupt the flow of information no matter how it is transmitted including:

• E-mails	• Web sites
• Texts	• Social Media e.g. Facebook, Twitter, LinkedIn
• Mobile phone / Telephone	• TV / Radio
• Personal radio	

Commanders need training to understand what tools and techniques they have available to disrupt information flow between adversaries or even the population. In addition, they need to understand the importance of protecting studios for broadcast systems such as TV and radio to ensure that they are not overrun by adversaries who could send out their own messages. Where adversaries have the capability for sending out broadcast messages the commander needs to use their ability to jam the signals. Web sites providing official information need to be properly protected against cyber-attacks. Conversely, web sites promoting anti-government information need taking down.

3.0 5 LAYER COMMUNICATIONS MODEL

Figure 5 shows a logical mapping of different aspects of the battlespace onto 3 orthogonal domains.

Environment Domain – Represents the physical location and state e.g. operating/destroyed, of entities (platform and people) and infrastructure e.g. communication network, in the real and synthetic environment.

Cognitive Domain – Decision making by EXCON, exercise participants, role players either by real people or using Artificial Intelligence (AI);

Information Domain – Information flow through communication system;

The Representation of Information Warfare effects in the Synthetic Battlespace

A key facet of the model is that the inclusion of an information warfare capability doesn't disrupt the way existing '2 dimensional' simulations currently operate.

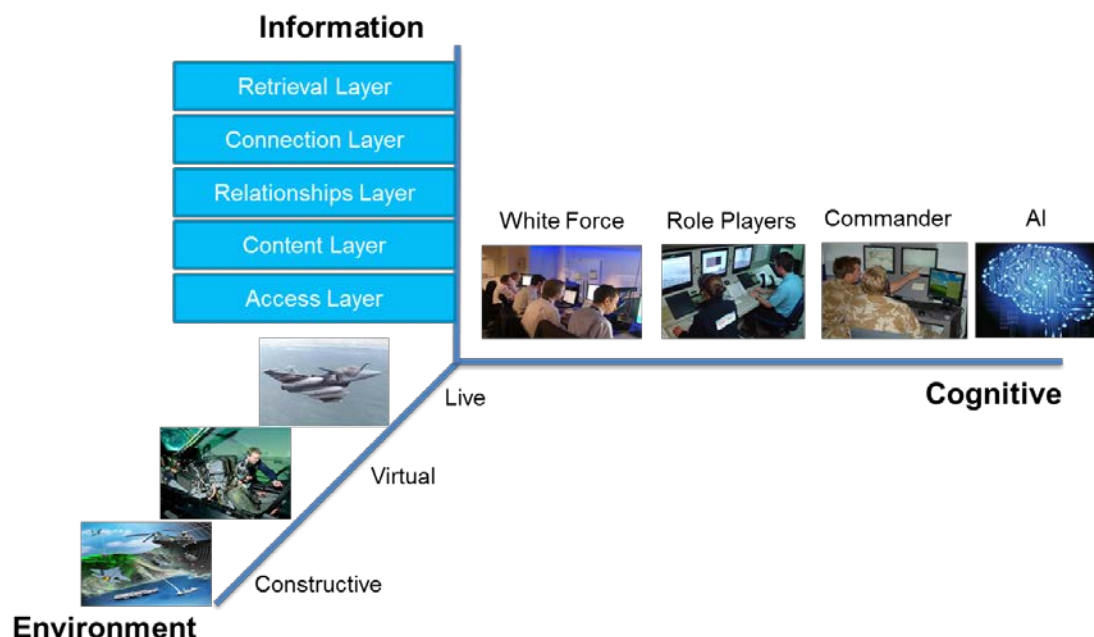


Figure 5 3 Axis Battlespace Model

The Environment domain includes operational C2 equipment and any physical infrastructure used by an exercise. The synthetic environment provides a wrapper to extend the physical environment of the HQ and represents all entities and infrastructure in the battlespace. Sensors in the synthetic environment typically stimulate the operational equipment used by the war fighters in the HQ. With respect to information warfare, the environment layer is responsible for representing the physical elements of the communication systems. These include the laydown of the communication bearers in the terrain e.g. copper or optical fibre cabling, intermediate network elements such as communication towers and the physical location of operator terminals. The Environment domain provides the means for disrupting communications using kinetic effects e.g. ordnance falling or being planted close to communication equipment that will render it inoperable. It also determines if a person represented by a CGF has an appropriate device for sending a communication e.g. are they carrying a mobile phone.

The Cognitive domain is where information from the Environment and Information domains is received and where decisions are made. These are made by commanders in the HQ who are endeavouring to accomplish the goals of the exercise. The EXCON may decide to introduce effects to challenge the commander and role players will make decisions to achieve the objectives they have been given. To reduce the number of white force players (i.e. all those supporting an exercise), which can be very costly, the use of more advanced AI techniques is being exploited in simulation environments.

The Information domain takes into account and isolates the factors that can disrupt the flow of information in the operational space. It is applicable to messages sent by any real or constructive people participating in or supporting an exercise and all the different forms of communication media.

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A prerequisite for a person to be able to send or receive a message is that they must have access to either physical or simulated communication equipment, which would be represented in the Environment Layer. Information flows from the sender’s communication equipment through to the Connection Layer and then to the receiver’s communications device also represented in the Environment Layer.

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The Access Layer determines that when a person wants to communicate with somebody else, both sender and receiver have access to a suitable communication device. This can be achieved automatically by interrogating the Environment to determine the location of the communication equipment and people using it. The output from the Access Layer service is True /False corresponding to whether the communication can occur or not.

3.2 Content Layer

The purpose of the Content Layer is twofold; to provide the ability for the name of the recipient or sender to be changed and to change the content of a message without the sender or receiver necessarily knowing what has happened. This enables the effects of spoofing to be simulated, which is the forgery of an email header so that the message appears to have originated from a legitimate sender rather than the actual

fraudulent source. Information about people such as mobile numbers for texting, e-mail addresses, social media usernames and passwords is commonly obtained using social engineering tactics. E-mail spoofing is a popular tactic used in phishing and spam campaigns because people are more likely to open a communication when they think it has been sent by a legitimate or familiar source. The goal of email spoofing is to get recipients to open, and possibly even respond to, a solicitation [6]. A spoofed email may also include a link that installs malware on the recipient's device if clicked.

The Content Layer also enables the content of the message or web site to be corrupted by simulating attacks on the communication system. Making parts of the message unreadable could lead to misinterpretation of the message resulting in commanders making incorrect decisions. If the communication system is compromised by an adversary, the tactic of subtly changing the content of the message may be used to tarnish the image of the impersonated sender e.g. peace keeping force. This capability could be used to alter the mood of enhanced behaviour models.

A simple Content Layer service would store a message in a queue to be manually processed and forwarded by the HICON or LOCON. This will enable them to change the message header or content so they are commensurate with the objectives of the exercise. The use of AI techniques to understand the message content may in future provide some form of automatic or at least semi-automatic way of changing the content of the message. The fidelity of the spoofing attacks to be simulated will be dependent on the objective and scale of the exercise being performed. However, it is conjectured that in most situations it will not be necessary to actually represent the content of the message but only its effect.

3.3 Relationship Layer

The Relationship Layer defines which people are able to communicate with each other. For text messages and e-mails it would define who is in their list of contacts. For social media it would specify what groups they are associated with. This function influences how messages are spread throughout the populace when sent to many people in an address book.

The input to a Relationship Layer service could simply access a spreadsheet that contains the names of the key players in the exercise, who is in their contact list and what groups they belong to. A more sophisticated implementation could implement it as a relational database. When a message is received, the Relationship service would check the message header to see if the sender and receiver are known to each other. If not, the message is discarded and not passed onto the Connection Layer.

3.4 Connection Layer

The Connection Layer controls the ability to transmit a message as a result of the interconnections and operational state of components in a communication network. This includes the communication bearers e.g. copper cables, optical fibre, and network components such as access points, switches and servers. Key components in the Connection Layer should have a corresponding representation in the Environment domain. This is to enable these components to be destroyed or disabled by activities that take place as the scenario unfolds.

Connectivity can be affected by several effects including:

- Loss of power;
- Elements of the network infrastructure being destroyed;
- Electronic warfare e.g. jamming;
- Loss of line of sight e.g. between VHF transmitters/receivers;

- Weather e.g. affecting atmospheric propagation of the electro-magnetic spectrum;
- Cyber-attacks e.g. denial of service.

The Connection Layer is initialised by storing the physical location of all the network elements being modelled and key personnel (constructive or role player) participating in the exercise. During an exercise, it receives the status of the communication equipment i.e. operating/destroyed from the Environment domain. It also receives the updates to the location of mobile communication devices and that of key personnel. This is important as it is used to determine whether a person has the means and is able to communicate with somebody else in the exercise. This could be due to being out of range or not having line of sight to a communications tower, or they are not next to or are carrying a communications device. For people speaking to each other without the aid of any communication equipment, the connection layer determines if they are physically close so could reasonably be expected to talk to each other.

COTS and open source network emulators are currently available that provide the required functionality for representing communication networks. These can be interrogated by a Connection Layer service to determine if there is connectivity between two communication devices. In order to degrade the transmission of a communication signal due to low bandwidth or jitter, the output from operational equipment can be passed through a network emulator.

Communication systems can be very complex with redundant paths and elements to provide resilience. However, it should always be borne in mind that the simulation should not be more complex than is needed to represent the desired effect. For some exercises, a realistic simulation of the key components in a network may be required to represent the effect of a denial of service attack overloading a server. In other exercises it may only be necessary for the EXCON to inject an event stating that a cyber-attack has taken place and that no messages will be transmitted through the Connection Layer.

3.5 Retrieval Layer

The Retrieval Layer simulates the real world latencies related to when people receive and process messages. With respect to receiving text messages on mobile phones, this could be because someone has their phone on 'Do Not Disturb' or they just miss the notification. When messages are propagated by social media e.g. Facebook, it can represent the delay in reading and forwarding messages. For information spread via web sites, the latencies relate to how often people would look at a particular page. For broadcast messages, it corresponds to whether someone or a group of people is watching or listening to the TV or radio (in this case, the message would either be received or not received).

The requirement of a Retrieval Layer service would be able to control the delay before the message can be accessed by the communication device. The delay could be produced using a random number generator that is initialised to control a delay profile for each participant and/or message.

4.0 SCORE EXPERIMENTATION

SCORE experimented with how existing and new services could be combined to represent Information Warfare effects in a simulation.

4.1 Degradation of Communications Using Real Equipment

To demonstrate how the performance of real operational equipment can be degraded in an exercise the communication path for a Skype call was routed through a network emulator. The network emulator provides the ability to degrade the signal by altering the amount of jitter and latency experienced by the transmitted data. This manifested itself as a poor quality video and voice, which made it harder to

communicate. The communication link was finally lost when the latency was too great.

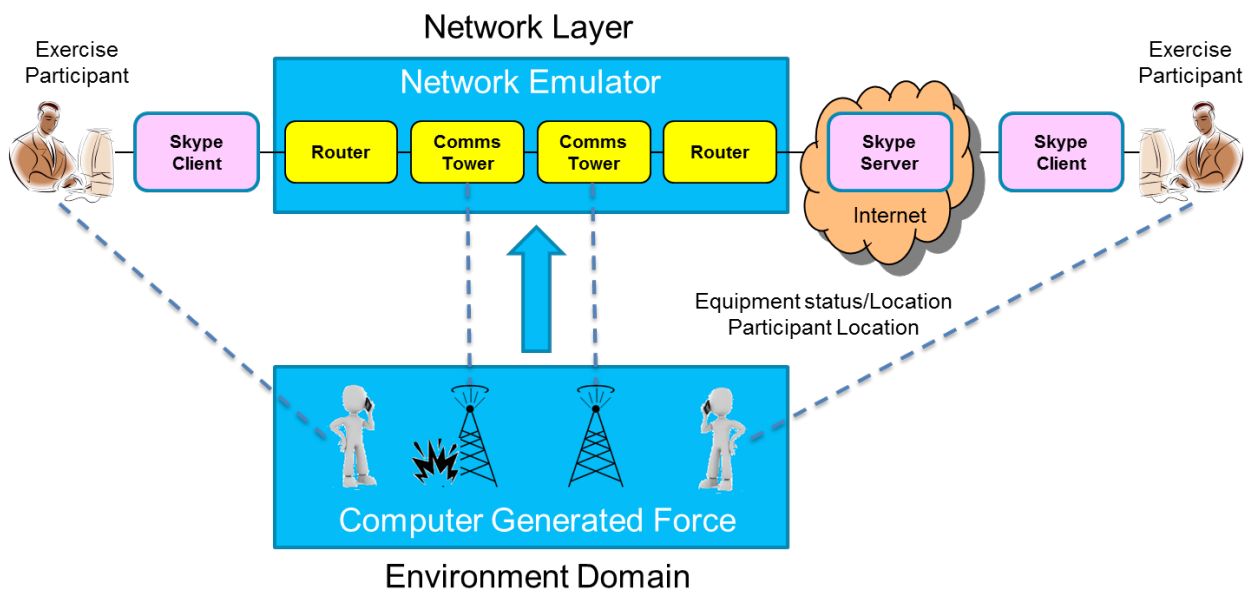


Figure 6 Degradation of Communications Using Real Equipment

The network emulator had an Application Programming Interface (API) that enabled the attributes of communication elements being modelled to be controlled programmatically. This ability was used to control the status of a communications tower and to change the location of the sender and receiver. As the sender and receiver moved out of range of the communications tower, as determined by the CGF, the Skype signal was lost. It was also lost when a kinetic effect represented by the CGF in the Environment domain caused one of the communications towers to be destroyed. In addition to video and voice calls, the approach is also applicable to sending e-mails and texts.

4.2 Message Propagation

The Message Propagation experimentation explored the use of a Connectivity service to determine connectivity between two entities by interrogating a network emulator (Figure 7). This was used to demonstrate the effect of a text message being propagated around a group of people. In this case the message is not actually sent through the network emulator but the ability to send message is indirectly affected as a result of there being a path between the sender and receiver or not.

During initialisation, the actual position of 3G/4G base stations in the area of interest, which was derived from government data, was downloaded to the network emulator. Entities were created in the network emulator to represent people in the scenario that had mobile phones and their location was updated in real-time by the CGF.

SCORE developed a Propagation service that could be configured to represent latencies related to when people would have read and forwarded a message. The Propagation Service provided the identity and location of the sender and receiver as inputs to the Connectivity Service. This interrogated the network emulator to determine if people represented in the CGF were within range of a 3G/4G base station to be able to receive or send messages.

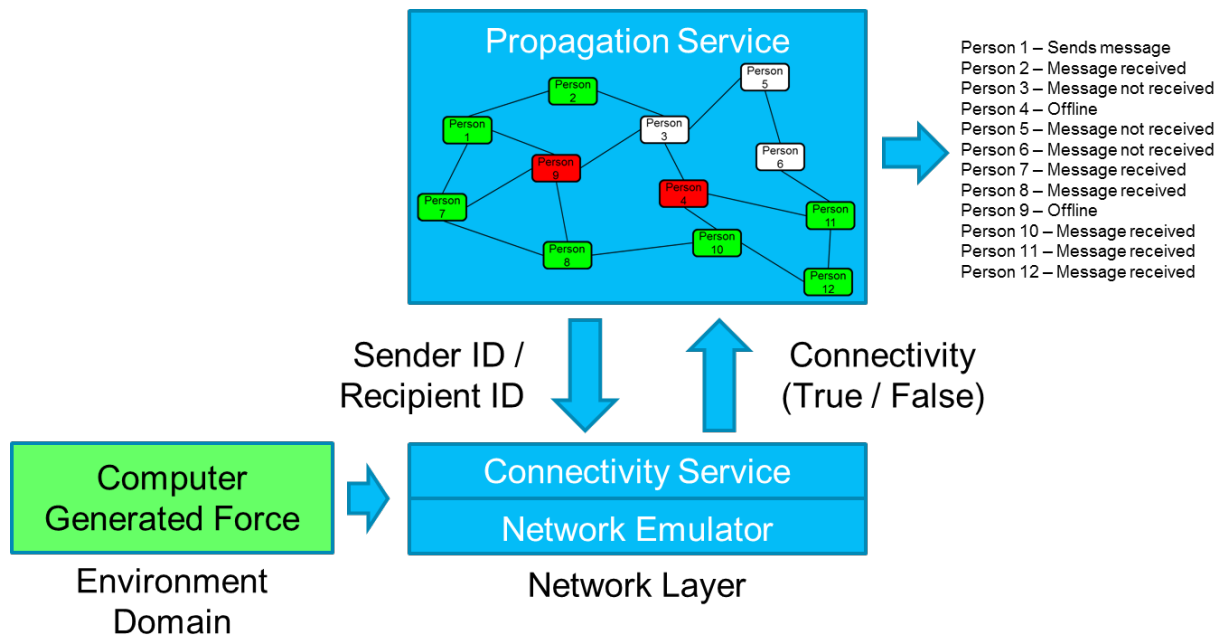


Figure 7 Demonstration of Message Propagation

The Propagation Service was initialised with random delays to represent when a person looked at a message and when they forwarded it. To demonstrate propagation delays, the Propagation Service displayed icons, representing the people in the scenario, which changed colour when messages were received. As people moved around they would come in and out of the range of the base stations and their icon turned red until connectivity was re-established and green when they received a message.

The Connectivity service was integrated with the CGF using the High-Level Architecture Evolved (HLA-E). By isolating the network emulator from the rest of the simulation, it has the advantage that if a different network emulator was used, it is only necessary to add another interface to the Connectivity service and it is not necessary to change the interfaces of other services that require access to it.

5.0 CONCLUSIONS

The current generation of Simulations and Synthetic Environments (SEs) focus on physical warfare effects and do not adequately represent the wider spectrum of activities in the operational environment. In order to provide a more realistic environment, the next generation synthetic battlespace must include a better representation of other aspects of operations including information warfare, infrastructure, logistics, human behaviours/interactions and the number of people represented in a simulation. The future synthetic battlespace must also enable synthetic entities to change their behaviour as a result of the information they receive through sources such as web sites, social media, television and radio.

The inclusion of information warfare effects greatly increases the realism for simulating the modern operational space as it can better represent the ‘fog-of-war’. In future simulations, when a commander sends an order, it cannot be assumed that the recipient will receive it immediately or at all. It might even be that the message itself has been interfered with. The inclusion of more representative communication models will increase the scope of training that can be performed. The SCORE experimentation showed that it is possible to provide an information warfare capability by integrating new capability to the existing approach to simulation, which enables it to be retrofitted to legacy simulations.

The 5 Layer Communication Model described in this paper extends the TTCP JSA2 KTA 3 model by providing a structured approach to degrading and corrupting communications. It is relevant to all types of communication media e.g. e-mails, texts, social media. Isolating the factors that affect the ability to transmit messages into these layers facilitates a more representative method of disrupting communications than can currently be represented in simulations. It also has the advantage that each factor can be changed independently and that the effect is automatically propagated to any other services that use communications. As an example, if a communications component e.g. communications tower, is immobilised by physical or cyber effects, it will not be possible for any communication devices using that network element to be able to pass messages (unless there are redundant paths).

The communications model is a logical model and that there does not have to be a one-to-one mapping between the different layers of the communications model and the services/applications providing the required functionality. For example, as some CGFs are now able to represent networks as well as entities such as people and platforms, the functionality provided by the CGF may span several layers. The provision of the functionality required by each layer of the communications model could be provided as a service, which is commensurate with NATO desire to provide Modelling & Simulation as a Service [8]. The services should have a user interface so that their effect can be manipulated during an exercise by the white force but more importantly, they should have an Application Programming Interface (API), to enable changes to be made programmatically.

The inclusion of information warfare in a simulation means that in future, scenarios will need to support additional data types e.g. for defining network topology. Further research is needed to identify the functionality required by services supporting the 5 Layer Communications Model, and to agree standards for exchanging information. Where possible, existing standards should be employed such as the use of Shape files for defining the physical routing of the network infrastructure and Digital Terrain Elevation Data (DTED) for defining the terrain. In future, network emulators need to be able to receive and respond to weather effects using the standards being defined by MSG-156.

There is an old adage that says ‘every model is wrong, but some are useful [7]. The art of simulation is just providing sufficient fidelity to satisfy the requirements without producing a ‘gold-plated’ solution. Whilst the need to be able to better represent information warfare effects in simulation environments has been recognised, the solutions employed can be very different. The criteria for what kind of solution is to be employed, is very dependent on the effect it must achieve. In some cases, it may be sufficient just to block a message getting through or it may only be necessary to simulate the effect of sending a message rather than its content e.g. it changes someone’s allegiance. If the timing of a message is important to an exercise then a more sophisticated simulation is required to represent latencies in the transmission and receipt of messages. Future systems for providing Information Warfare training should be able to represent all the tools available to a Commander and the effect of their actions or inaction; did it prevent or cause an attack taking place, has it reduced or increased tensions in the population did they target the correct person or group of people?

The SCORE experimentation demonstrated different solutions for implementing the 5 Layer Communication Model; communications could be degraded by passing information through a network emulator or its output used indirectly to affect communications. The approach to be used in an exercise is dependent on the type of communication being transmitted and the requirements for the simulation. SCORE demonstrated that by passing information through a network emulator, it is possible to degrade e-mail and text video/voice streams sent via operational equipment that is used in an exercise. This enables communications in the chain of command to be disrupted i.e. between a Commander and the HICON/LOCON, and between other participants in the exercise.

The inclusion of information warfare effects in a simulation will require more advanced behaviour models for constructive entities so that they can respond to the effect of the communications. These would be associated with the Cognitive domain. SCORE demonstrated the use of a ‘Disposition’ service that altered

the mood and allegiance of constructive entities depending on the information they received [5]. In the future, constructive entities rather than the LOCON should be able to automatically generate messages that create the background traffic that are used to mask important messages that a Commander should react to.

The SCORE experimentation has shown that the High-Level Architecture (HLA) and Distributed Interactive Simulation (DIS) are appropriate for communicating the location of entities from a CGF to a network emulator. The use of network emulators will provide a quick-win for representing the disruption of communications in simulations. It is recommended that new standards should first focus on producing a standard for initialising and controlling network emulators as there is a danger of a plethora of proprietary standards emerging for these tools. SCORE demonstrated the use of a network service that could be used to provide a common interface to different network emulators, which could provide an intermediate solution until standards become available.

As well as the network emulators representing communications networks, they could also be used in future to simulate utilities such as power distribution and water networks. Infrastructure such as electricity sub-stations and pumping stations could also be represented in the Environment Layer. The effect of these utilities not being available could be used to negatively affect the mood of the populace, which could change the outcome of an exercise.

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Introduction of Unmanned Airborne Combat Systems into Future Threat Scenarios: Opportunities and Challenges

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ABSTRACT

In future air combat, the integration of unmanned cooperative systems will be a potentially huge force multiplier. Key factors for its success will be teaming intelligence, coordinated mission planning and cross-platform mission management. Therefore, the task of conceptualizing the next generation airborne weapon system requires a holistic system-of-systems approach that considers the different air vehicles itself, their avionics mission systems and the overall concept of operation against future threats. For early validation of possible solution concepts and assessment of their operational performance, a dynamic multi-agent combat simulation has been developed over the last years within Airbus Defence & Space Future Projects. In addition to its faster-than-real-time engineering functionality, the simulation allows real-time human-in-the-loop experiments to foster collaboration between engineers, operators and customers. This paper presents our approach to dynamic mission simulation and insights from the application of our tool during the Future Combat Air System (FCAS) studies, during which it became clear what will be a key challenge for future applications: Implementing a robust high-level planning algorithm that generates ad-hoc mission plans for complex air operations while considering reactive low-level agent behaviour, human operators and online user input.

1.0 INTRODUCTION

Every new fighter generation can be defined over one or multiple technological leaps that significantly discriminate the design of its members from the ones of the previous generation. It is without doubt that there have been significant advances in almost all design disciplines since the first 5th generation fighter aircrafts entered service about 15 years ago. Different aircraft manufactures, including Airbus, have already announced that they are currently conceptualizing or working on 6th generation fighter jets [1] [3]. Compared to current state-of-the-art aircrafts, those projects will very likely see improvements in various fields like flight performance, all-aspect and all-modality stealth, low probability of intercept radar and communication or armament. Still the question remains: What will be *the* defining factor of this generation, a true game changer for the battlespace of the future?

A common assumption is that the future battlespace will be “highly networked”, i.e. all involved entities can exchange their situational view and create a shared tactical picture in near real-time. On the one hand, this enables reliable spatial and temporal synchronization of multiple platforms to a degree that has previously not been possible. Many algorithms, especially for emitter localization or target ranging, produce significantly better results if measurements can be generated from multiple positions. On the other hand, a reliable exchange of high-quality data allows more tactical flexibility by distributing tasks that have previously been carried out by a single platform. The major application for combat aircraft is probably the so called cooperative engagement concept (CEC), which is already part of the U.S. Navy’s Naval Integrated Fire Control-Counter Air (NIFC-CA) doctrine against anti-access/area denial (A2/AD) environments [4], but other applications are also possible, e.g. cooperative electronic attack. The mentioned concepts are mainly

applicable in the short-term context of a single situation during a mission, e.g. reconnaissance or attack of a SAM site, air-to-air (A2A) combat, etc. However, there is also another aspect with respect to mission as a whole that should be mentioned. Given reliable communication between all involved entities, planning algorithms can exchange proposals for mission plan changes and automatically accept or decline them based on their objective and current tactical situation. This is especially useful in situations where one or more unforeseeable events render the original mission plan invalid despite all pre-calculated margins. Instead of estimating if an alternative plan is feasible and aligning it with all other entities via voice communication (which is a challenging and time consuming task given the high workload of the crew during some mission phases and the number of involved entities), a cross-platform mission management system can quickly calculate alternatives to the current mission plan and evaluate if e.g. temporal constraints like open corridors can still be met. A set of alternatives is then presented to the crews to support their decision if and how the mission can be continued.

Combining the above ideas with the now available on-board computing power, made possible by recent advances in both hardware and software, it can be concluded that the coming fighter jet generation will very likely operate with superior tactical concepts based on powerful avionics systems and fast and reliable data exchange. However, this is not yet the definite game changer we are looking for – even existing 5th generation fighter jets already apply some of the mentioned concepts, e.g. the F-35 within the NIFC-CA context [4]. Consequently, the next step is to not only improve the avionics of the aircraft but to coherently optimize avionics, tactics and platform design under the premises of a fully networked environment. This approach allows thinking about concepts where not every platform needs to have a full sensor suite and full decision making capability if it is supported by complementary entities within the network. As a consequence, different platforms can be highly optimized to their special tasks, thus reducing the number of trade-offs required in the design process compared to the “single platform does it all” approach. It is quite obvious that a dedicated sensor platform needs no or very limited armament, so the now available space can be used for better sensors or larger fuel tanks. This can already lead to a significant performance improvement for the tasks the platform is specialized on, but there is one thing that can be removed that has the most impact: The pilot. At this point, it has to be clearly noted that there is currently no algorithm or artificial intelligence that comes even close to the situational awareness and decision making capability of a trained aircrew. This is why a human pilot will always be necessary for combat missions in the near future. However, the pilot (or more precisely, the decision maker) does not need to be in the same platform if he/she is provided all required information for commanding his/her unmanned companions. We therefore propose a concept in which one or more manned platforms are supported by multiple unmanned and specialized combat aerial vehicles (UAVs). In the following, we will refer to a group of at least one manned platform and one or more specialized UAVs commanded by the manned platform as package. We claim that the unmanned platforms will function as a force multiplier for the manned platforms due to the following reasons:

- UAVs are expandable and aircrews are not. Thus, UAVs can perform high-risk tasks and allow tactics that would not be acceptable with manned platforms only.
- UAVs are cheaper (even when not considering the value of the crew) because they can be built smaller than manned platforms with same performance. This means that more platforms can fly a mission at the same cost and a higher number of platforms lead to a higher mission success rate: First, because there are more redundancies and second, because some tasks can be performed better if more assets contribute to it, e.g. emitter localization.
- Different UAVs and manned platforms can be combined arbitrarily. Before the start of a mission, packages can be composed as required. During the mission, packages can also be recombined given certain constraints, e.g. maximum distance between the command platforms if the rules of engagement prohibit uncontrolled flight. This allows for greater flexibility in mission planning and execution and is expected to also keep operating costs and material wear low (“use only what you need”).

As always, there is no such thing as free lunch. In our case, all the above advantages come at a cost for the aircraft designer: Instead of optimizing the performance of a single design to a set of technical requirements, multiple platforms and their subsystems have to be designed such that they maximize the overall system-of-systems performance in various missions and package configurations. In the remaining part of this paper, we will present the FCAS Prototyping Lab (FPL), a simulation environment developed in the FCAS context to tackle this highly complex problem. After outlining its role in conceptual design and interdisciplinary technology prototyping in chapter 2, we will present the concept and architecture of the underlying dynamic multi-agent mission simulation in chapter 3. In chapter 4, results from selected projects are presented to outline the versatility of the tool. The paper will be concluded with what might be one of the biggest future challenges not only for simulation but also for the introduction of unmanned systems in general: Implementing a robust high-level planning algorithm that generates ad-hoc mission plans for complex air operations while considering reactive low-level agent behaviour, human operators and online user input.

2.0 CONTRIBUTION

From a functional perspective, the FPL is an analysis tool for the conceptual design of aircrafts and their subsystems. Many already existing tools are used in the aircraft design process to calculate different performance measures of the platform itself (e.g. range, climb rate, manoeuvrability etc.) or for its subsystems (e.g. sensor range and coverage, datalink bandwidth etc.). However, those tools are often stand-alone and cover only some aspects of the aircraft's mission. Based on year-long experience of engineers and designers it is possible to combine results from all those tools to maximize the expected mission performance of a new aircraft design. This becomes increasingly complex when not only a single platform concept but different platform and/or subsystem concepts have to be considered in a holistic system-of-systems context. To handle this increase in complexity, the FPL can be used to assess the operational system-of-systems performance by simulating complete combat missions in a highly dynamic environment. Platform and subsystem performance measures calculated from different design tools can be used as input for a detailed physical simulation of current systems and future concepts. Different operational performance measures allow to assess how changes in the concept affect the overall mission success.

Furthermore, the FPL is not only used for internal analysis as it also provides a transparent way to translate customer needs to technical requirements. In the early stages of conceptual design, requirements are usually very limited. It is however very crucial to the success of a product to have a common understanding between customer and manufacturer regarding the desired functionality and how this functionality can be realized. To this end, the customer may define exemplary missions that a future aircraft should perform. Relevant aspects of those missions or even complete missions can then be simulated in the FPL. Measuring the performance of different concepts in those missions helps the customer and engineers to jointly evaluate the impact of different design trade-offs. Based on those evaluations, more detailed technical requirements can be formulated that are traceable back to operational customer needs.

The dynamic mission simulation is the core component of the FPL, but the full scope of the FPL goes beyond that: It is in fact a physical environment with different human-machine-interfaces (HMI) like cockpits or command stations that can be used for human-in-the-loop experiments. Those experiments may range from testing different HMI concepts with a single pilot up to facilitating complete wargaming sessions with multiple operators on own and enemy side. In addition to that, the architecture is based on open-source middleware and designed to allow fast integration of new simulation models in a "plug-and-play" manner. In sum, this makes the FPL a powerful rapid-prototyping tool to foster cooperation between different disciplines and stakeholders. By involving industry partners, experts from different disciplines, customers and operators in early phases of aircraft technology projects it is ensured that novel concepts are assessed from different viewpoints and that all important aspects are covered.

3.0 METHODS

The core of the FPL is a dynamic multi-agent mission simulation which can be run on a single computer or distributed over multiple machines and with different additional hardware components. To facilitate wargaming sessions, to prototype and test HMI technologies or for general demonstration purposes, all manned airborne assets in the simulation can be optionally controlled from hardware cockpits. If no human operators are involved, the simulation has to be capable of running faster than real-time. This is especially required for effective development and trade-off analyses in large-scale missions that might take up to hours. To assess concepts and technologies in an objective and unbiased manner, the course of every simulated mission evolves from pre-defined system properties, simulation of physical effects and configurable agent behaviour and cooperation. There exist no scripted events and the result of every new simulation run is completely open. Blue and red forces are simulated under the same assumptions and with comparable level of abstraction. The following chapters outline how missions of current and future airborne systems can be dynamically simulated in the FPL. We present our simulation architecture, the most important design trade-offs when modelling such systems and a high-level planning/low-level control approach to behaviour modelling.

3.1 Architecture

The simulation architecture of the FPL consists of three logical components: Applications, simulation control and communication middleware. A central feature of the architecture is that the simulation is split into several applications. Every application runs different models, e.g. there is an application for simulating own (blue) air vehicles, enemy (red) air vehicles, an integrated air defence system (IADS) and many more as shown below. All applications share the same standardized interface and can be combined arbitrarily. This modularization allows running only a selection of models that is required for a certain task or project. All applications are stand-alone executables and can be run in parallel processes on the same computer or distributed over several machines. By exchanging compiled binaries, the integration of models from different companies is possible without exposing the detailed underlying functionality. Fast and easy cooperation between different companies is in general a main driver for the FPL architecture. To this end, a base application class is made available that provides all simulation-related functionality like simulation control state machine, communication middleware interface and common libraries e.g. for geospatial calculations in different coordinate systems. New models can be added to the simulation framework by simply implementing a new base application instance. The execution of all applications is controlled by a central simulation control instance. It provides a graphical user interface to start, stop and speed up the simulation as required. During execution, the runtime of all applications is monitored and the simulation time is dynamically adjusted to the slowest model. This allows distributed faster-than-real-time simulations with adaptive simulation time acceleration. Communication between applications is realized with the Data Distribution Service (DDS) standard [2]. It enables reliable and scalable data exchange in a network using a publish-subscribe pattern. Two different partitions are used for broadcasting simulation data (e.g. entity states, simulation control commands, etc.) and multicasting command and control data (e.g. data actually sent over BUS-systems or data links). An open source implementation of the DDS standard is used to further ease collaboration with external partners.

Figure 1 provides an overview of our simulation architecture including applications that are required for most missions. As previously mentioned, this architecture is not fixed and virtually any application can be removed or exchanged as required. New models can be integrated by registering a base application implementation at the simulation control via the DDS middleware as indicated by the dashed black arrow. Boxes with blue/red background depict own/enemy systems, boxes with mixed colour can be used by both sides. Simulation infrastructure components are coloured grey and user interfaces are coloured orange. Black arrows indicate communication during the simulation, grey arrows stand for data exchange before/after a simulation run. The high-level functionality of all applications shown in *Figure 1* is listed in *Table 1* below.

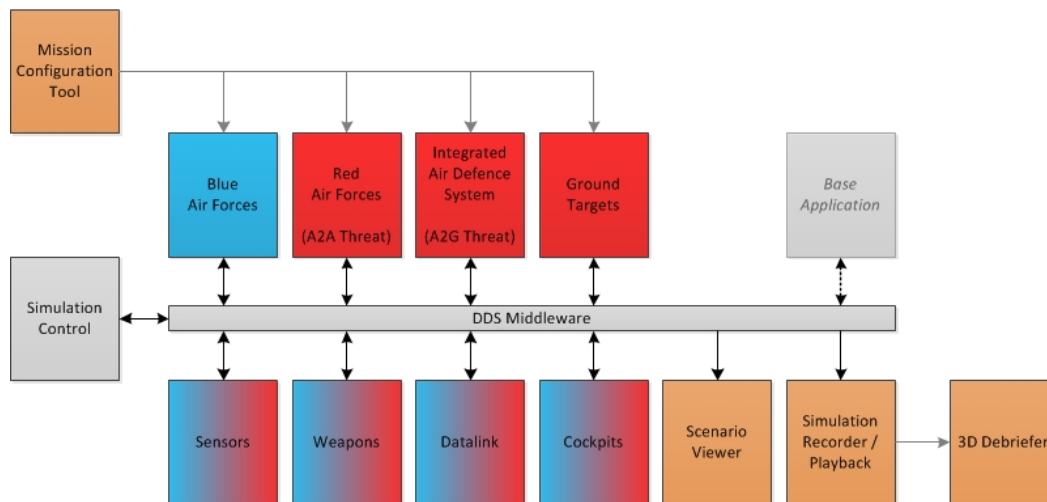


Figure 1: Architecture overview with baseline components.

Table 1: Selected applications and their high-level functionality.

Application	Usage	Functionality
Mission Configuration Tool	Setup	Graphical user interface for setting initial configurations of blue and red forces, mission planning
Scenario Viewer	Visualization	Online mission visualization
Simulation Recorder / Playback	Analysis	Record mission data during simulation to playback missions later for debriefing and further analysis
3D Debrief	Visualization	3D visualization of recorded missions for debriefing
Blue Air Forces	Blue Forces	Airborne system simulation including 10-DOF* aerodynamic model, flight control system (FCS), manoeuvre logic, sensor models, data fusion and tactic module
Red Air Forces	Red Forces	Air threat simulation including 10-DOF* aerodynamic model, FCS, manoeuvre logic, sensor models, data fusion and tactic module (A2A only)
Integrated Air Defence System (IADS)	Red Forces	Ground threat simulation including ground-based radar simulation, vehicle motion, data fusion and tactic module
Ground Targets	Red Forces	Static and moving ground targets not integrated in the IADS
Sensors	All Forces	Radar simulation including detection model, radar management and target tracker model; passive emitter localization, EO/IR

Weapons	All Forces	A2A, A2G and G2A weapon simulation including gun model, missile propulsion model, 5/10-DOF* aerodynamic model (missiles and guided munition), seeker head model, guidance laws and damage assessment
Datalink	All Forces	Multi-platform information exchange system, radio simulation
Cockpits	All Forces	Physical cockpit models to optionally take over control of aircrafts from UCAV or interceptor application

* Aerodynamic models with 10 degrees of freedom (DOF) for aircrafts and cruise missile types, 5 DOFs for missiles (roll not simulated).

For wargaming sessions, the different applications run distributed over multiple rooms in the FPL to mimic the procedure of real air operations: After setting up a scenario, operators on blue and red side use the mission configuration tool to plan their mission in separated rooms. The air operation commanders remain in those rooms while pilots split on two rooms with two cockpits each to fly the mission. Any aircraft from the blue and red air forces application can be controlled from the cockpits, so pilots can take over different roles and fly against each other or as a single team against computer controlled forces. All rooms are equipped with a voice communication simulation. After the mission, the teams come together in the briefing room to evaluate the mission which can be replayed from recorded simulation data. An additional room equipped with multiple PCs connected to the simulation network can optionally be used for project-specific tasks, e.g. hardware-in-the-loop experiments.

3.2 Model Building

The choice of the right modelling paradigm for the FPL is in fact not trivial as it covers aspects of an operational analysis tool (often stochastic) as well as an engineering simulation (usually deterministic or hybrid). The impact of this decision can best be illustrated on an example, namely how to determine if an aircraft is hit by a missile. In a stochastic model, this decision is based on configurable probabilities, e.g. probability of hit (missile) and evasive manoeuvre success (aircraft) and a random number. To make the final mission result less sensitive to a single random number, multiple simulation runs with different random seeds are often conducted in practice. Following the deterministic approach, the missile flyout is simulated based on the missiles' launch direction, guidance law and fixed performance parameters like thrust, maximum acceleration etc. The aircraft's trajectory during the evasive manoeuvre is analogously based on its initial state, aerodynamics, reaction time etc. The aircraft is considered killed e.g. if the distance between missile and aircraft is below a certain threshold when the warhead detonates. In a deterministic model it is per definition already known at the time of the missile launch if the aircraft will be hit. Necessary simplifications in deterministic models are usually done by introducing fixed parameters like the distance threshold in the missile example. Hybrid models allow using random numbers for such simplifications, e.g. a probability of kill as function of miss distance.

To efficiently test and analyse large-scale air operations, the simulation should run faster than real-time by at least factor 10 (on average) with several dozens of blue and red assets in operation on a single machine. This imposes a major restriction on time discretization and runtime complexity of the used algorithms. To also maintain rapid prototyping capability, the time required for setting up the simulation for new projects or developing/integrating new components should be kept low. Models that are too complex impose more restrictions than significantly improving the quality of the results. Under those aspects, (more) stochastic models have the advantage of being faster in both runtime and development time. However, there are two major factors that restrict the use of stochastic models to a minimum in our case: First, the simulation will only be accepted by operators if gives exact reasons why their tactics and manoeuvres were successful or not. Additionally, stochastic models are data driven, but the required data is often not available for future

own and/or enemy systems. It is possible to estimate the probability of kill for a missile that has been in service for years and shot multiple times in tests or real operations. It is however very risky to just increase this probability for future missiles, especially because stochastic models are very sensitive to those parameters. From our point of view, a sounder extrapolation of future systems can be achieved by modelling all systems as generic physical models based on technical system parameters. In a first step, the models itself are validated by simulating existing systems with known technical and performance parameters. For future systems, the technical parameters are then extrapolated based on expected technological advances, domain expert knowledge and their tools. To stick with the initial example, the extrapolated evasive manoeuvre performance of a future fighter is e.g. based on a higher lift coefficient calculated from CAD and fluid dynamic models or on higher resolution and sensitivity of the missile approach warner.

A key aspect for objectively evaluating the performance of future concepts in simulation is the modelling of environment and threats. It has to be taken into account that the system-of-system approach is leveraged on red side just like on blue side. The danger of modern IADSs comes from combining different systems from very short range to long range. All of those systems have their strengths and weaknesses, but they are organized such that individual weaknesses are compensated by other systems and overall system-of-system performance is maximized. The first difficulty is therefore that a large amount of systems has to be simulated and that the individual strengths and weaknesses of those systems have to be identified. The approach of generic physical models comes to use for both aspects: After a generic air defence system model has been developed and validated, it allows quickly integrating new systems in the simulation. Based on the simulated physical effects, operational strengths and weaknesses of enemy systems or possible future threat concepts can be estimated. The difficulty of using generic models on the other hand is that functionalities from real systems have to be mapped to the generic model such that all significant individual system properties are retained. This leads inevitably to quite complex and detailed generic models. We will outline our approach to balancing complexity and fidelity on the example of the ground based radar component. As exemplary shown in **Figure 2**, an entity within the IADS simulation is composed of different components. Those components can be combined arbitrarily to quickly configure new systems. From a functional point of view, the ground based radar component is made up of controller, detection model and target tracker. According to the current task of the entity, the controller selects the required radar mode, e.g. surveillance for 360° search or combat search if a specific sector has to be prioritized. To counter jamming or ground clutter, different waveforms can be used. Depending on the radar type, e.g. mechanically or electronically steered in one or two dimensions, the controller has varying possibilities to adapt the search pattern. After the types and numbers of waveforms have been selected for a beam position, the detection model generates measurements based on an aspect-dependent radar cross section model of the target, ground clutter, terrain shadowing, atmospheric attenuation and electronic countermeasures. Measurement errors are induced by signal-to-noise depending stochastic models. The hence generated measurements are then processed by the target tracker which performs measurement-track association and track filtering.

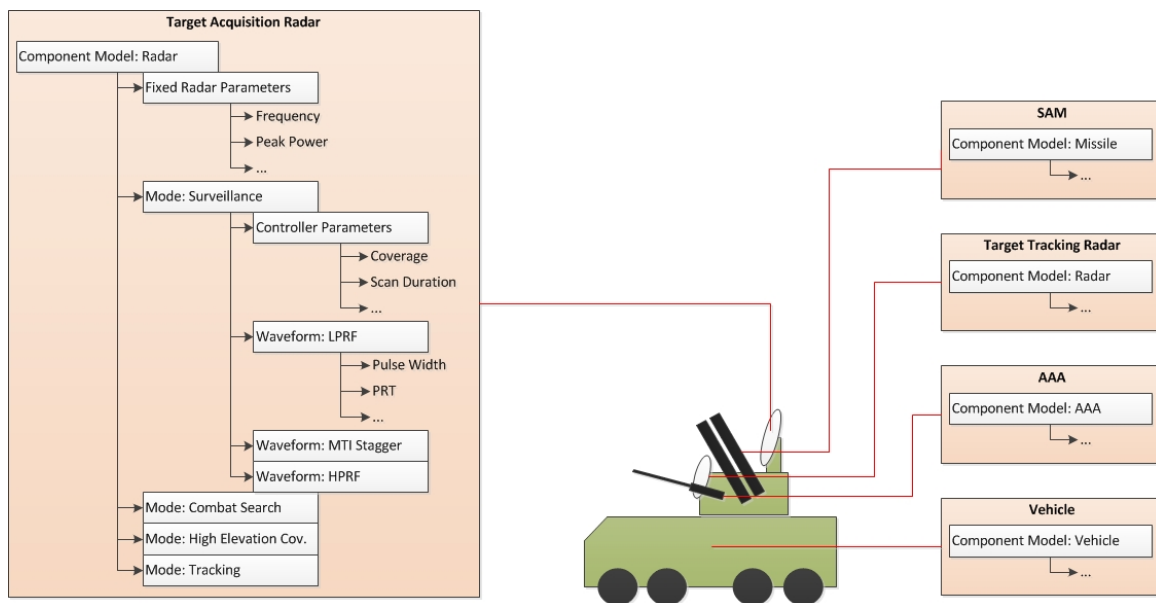


Figure 2: Exemplary mapping of a short-range ground-based air defence system to generic components.

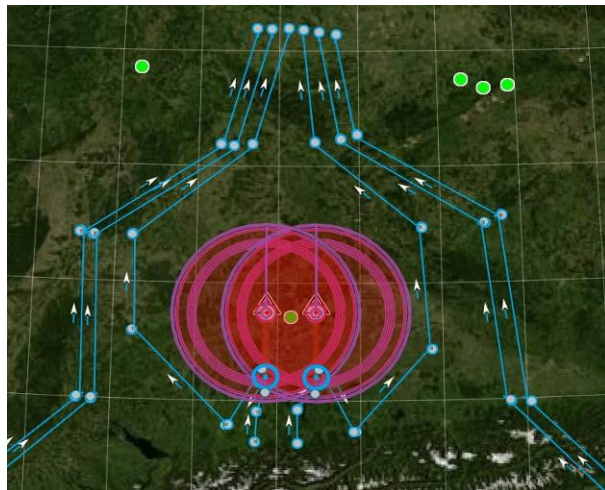
Another difficulty arising from such detailed models is the total number of parameters that have to be estimated. It is also important to note at this point that all data in the simulation is non-restricted. This is on the one hand due to constraints from most projects, but on the other hand it also has practical advantages in daily work. One has to keep in mind that the simulation is used for concept validation and not for detailed system design, so using classified threat data at this early stage would impose major restrictions to infrastructure and development processes without adding significant value to the results. Based on that, all threat data had to be estimated based on publicly available sources or non-restricted data from internal projects and external partners. This again led to a large amount of data which is often on a very different level of detail or inconsistent, e.g. due to de-classifying restricted data. With the continuous development of our models and the engineering expertise gained over many years, it was possible to estimate consistent parameters for different current and extrapolated future threat systems. This was mainly done in an iterative bottom-up process: Based on available technical and performance parameters, missing model parameters are estimated to fit the component performance. Behaviour and interplay between the different components of a single system is then tuned to achieve the desired system performance. Finally, coordination of those systems within the IADS is tested in different scenarios to maximize the overall system-of-system performance.

3.3 Behaviour Models and Coordinated Tactics

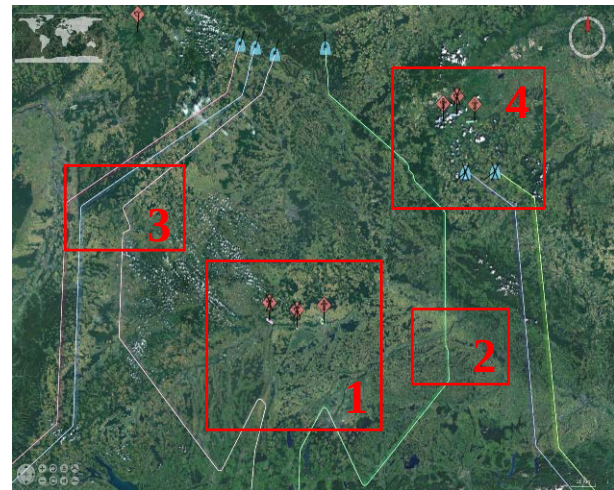
The topic of behaviour models has already been touched in the context of model building and threat simulation. Compared to the threat simulations, which are in most scenarios only reacting to blue force actions, the blue air force simulation requires a high-level mission plan to achieve the desired mission goals. In addition to the high-level mission plan, all agents in the blue air force simulation have a low-level behaviour model that defines how high-level tasks are executed based on the current situation and how to react to unplanned events. We will demonstrate the interplay between high-level planning and low-level agent behaviour on a simple example mission as shown in *Figure 3*. It has to be noted that this mission is mainly for illustrative purposes and does not necessarily reflect a realistic combat mission. The different red force components of the scenario are a known and alerted SAM site in the south, a pop-up threat in the north-east and a long-range surveillance radar in the north-west. Blue forces ingress from the south in 3 groups of 2 fighter aircraft each. The centre group is tasked to attack the known SAM threat before splitting

up and joining the other groups. To further illustrate temporal coordination between agents, all aircrafts should merge into a single formation after traversing the mission area from south to north. The above behaviour is defined in the high-level mission plan that consists of waypoints, pre-defined target and weapon assignments as it can be seen in **Figure 3a**. It is further possible to define e.g. sensor-optimized patterns or electronic attacks on pre-defined targets.

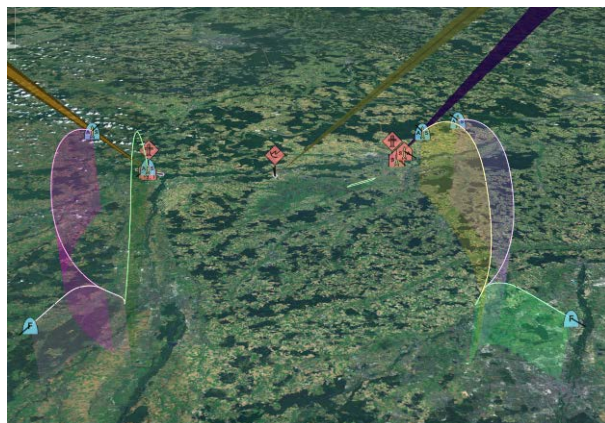
Figure 3b shows the actual course of the mission. Low-level agent behaviour can be explicitly observed in different mission phases that are framed red and numbered in chronological order. Mission phase 1, the attack on the known SAM site by the centre group, is shown in **Figure 3c** in more detail. Agents fly a weapon release manoeuvre that maximizes the energy of the released weapons based on target type, selected munition and pre-planned attack point before turning away to escape the SAM engagement envelope. It can further be observed how the target tracking radars of the SAM site track the incoming A2G missiles and multiple SAMs are launched for self-defence. This results in 2 of the 3 vehicles surviving the first attack. After having executed their attack manoeuvres, both blue aircrafts return to the pre-planned trajectory. Depending on the defined rules of engagement, a re-attack can simply be carried out if a radar is still emitting after it was attacked (as it is the case here) or it might require battle damage assessment with imaging sensors. In mission phase 2, the agent decides to re-attack the remaining vehicles in the SAM site. As the A2G missiles fired by the aircraft are again intercepted by the SAM site, another re-attack is carried out in mission phase 3. The assignment of such unplanned attack tasks is based on the prioritization of threats with respect to their estimated impact to own mission success and current role, remaining ammunition and relative position of all own assets to the target. **Figure 3d** shows the beginning of mission phase 4. This time, there is a tactical advantage for the red side: All incoming aircrafts are tracked by the long-range surveillance radar, thus the pop-up SAM is able to engage as soon as targets are in the no-escape range. As the radars of the SAM site switch on, their coarse positions are estimated by passive emitter localization and 3 radar-homing A2G missiles are launched in direction of the threat. It can be seen in **Figure 3b** that both outmost aircrafts have performed an evasive manoeuvre, but due to their tactical disadvantage and no simulated electronic counter measures they have been engaged by the pop-up threat in this scenario. However, the third aircraft of the right group is still able to successfully attack the target acquisition radar of the SAM site before returning to its pre-planned trajectory and merging with the other aircrafts as initially planned.



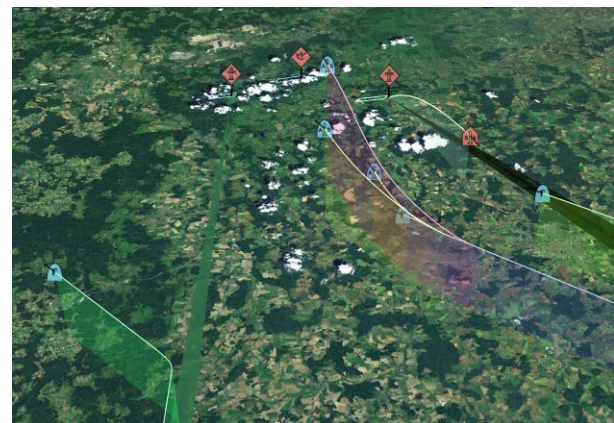
(a)



(b)



(c)



(d)

Figure 3: (a) Mission plan generation in the mission configuration tool. (b) Mission execution with 1. pre-planned attack on known SAM site, 2. and 3. re-attack and 4. pop-up threat. (c) Close-up view of pre-planned attack. (d) Close-up view of pop-up threat situation.

4.0 RESULTS

The FPL has already been used in different projects within Airbus Defence & Space or in cooperation with industry partners on national and European level over the last 10 years. Although those projects vary largely in their scope, unmanned systems have always been in focus. In the following, we present several stages and aspects of conceptual design in the context of FCAS and show how the FPL serves as versatile analysis and engineering tool on the way to the next generation airborne weapon system.

4.1 Technology Identification

Technology identification is a continuous process to monitor research and technology advances in aerospace relevant domains and to analyse their possible impact on design and operation of future products. On the one hand, it should cover all technologies that can be used to enhance the capability of the platform or its subsystems. On the other hand, it is at least equally important to deal with various other technologies that might affect the future operational environment and thus require different platform capabilities and

operation. Results from this process serve as starting point for new concept designs. Hence, they should answer the question: What are potential game changers for aircrafts that will be in service decades in the future and what technological gaps have to be filled to make those technologies fully available by that time?

Technology identification was also the focus of the early FCAS phases in a national cooperation involving the German armed forces and over 10 different aerospace companies. Besides other technological fields regarding aircraft design and operation, several key enablers for future air combat with unmanned systems were under investigations. The FPL supported those investigations by providing a testing and analysis environment for advanced mission planning, autonomous mission execution, communication management and minimizing emitting signatures. Results from those studies were used to shape technological roadmaps for research and technology activities and serve now as input for the European FCAS cooperation. The flexible “plug-and-play” and open-source architecture as outlined in section 3.1 was crucial for integrating various models from different industry partners in a common prototyping framework.

4.2 Concept Validation

The subsequent stage of FCAS is to conceptualize more concrete designs and analyse their operational performance in relevant mission environments based on the identified technological advances. As outlined in section 2, the FPL provides the operational analysis capability to perform design trade-offs in a holistic system-of-systems context. Together with our customer and industry partners, an exemplary mission that challenges different aspects of the concepts was defined to be simulated in the FPL from start to end. In an iterative process, the different concepts were evaluated in the selected mission and refined together with operators and customer representatives. The selected mission did not only impose several challenges to the concepts but also to the simulation itself. It required faster-than-real-time simulation of several dozen entities on blue and red side including a fully integrated future IADS that incorporates a variety of systems from short to very-long-range. Therefore, not only the blue side concept was subject to change, but the threat simulation was also improved based on input from subject experts from customer side and industry partners. Showing the simulation on various occasions led to a productive and interactive exchange about the expected performance and behaviour of future threat systems. As a result, behaviour models on blue and red side became more and more competitive and robust during the project due to changing behaviour on the opposing side. To guarantee unbiased results, blue and red side models were developed based on a common set of assumption and level of abstraction but by different teams and only with limited knowledge about the tactics of the opposing side. Next to the actual data generation for operational analysis, an important contribution of the FPL was to serve as basis for discussions between engineers, operators and customer. After several development iterations, the simulation environment and its modelling approach was accepted by the customer and could be used for the final assessment of selected concepts. From those assessments it can be concluded that the initially claimed force multiplication effect by unmanned assets as presented in section 1 can be supported by simulative results from the FPL.

4.3 System Prototyping

A key enabler for the successful use of unmanned assets in the different FCAS concepts is a cross-platform mission management system. This system serves two main purposes: First, it controls and coordinates mission execution of multiple UAVs. By automatically distributing tasks and planning manoeuvres it aims to maximize the operational performance of the whole UAV package while minimizing workload of the commanding aircrew. In contested environments with possibly limited communication between manned and unmanned platforms, the cross-platform mission management system needs to reliably control all unmanned assets such that they do not interfere with each other or the manned platforms. Additionally, the cross-platform mission management system serves as command and control interface to the aircrew. It has to receive high-level tasks from the aircrew and present plans to solve those tasks in a fast and intuitive way. With its capability to simulate multiple unmanned assets in future threat environments and the available HMIs for command and control, the FPL provides the environment for prototyping different concepts and

algorithms of the cross-platform mission management system. Based on a set of evaluation vignettes it could already be shown that the efficiency of A2G missions could be significantly improved when using highly-coordinated package maneuvers compared to conventional flight planning, e.g. for precise localization of threats with distributed sensors on low-cost platforms or cooperative approach and attack manoeuvres to exploit specific threat weaknesses. The so far tested algorithms include cooperative path planning and swarming approaches, but also more experimental approaches like reinforcement learning. This shows how the FPL with its faster-than-real-time simulation capability can be used as training environment for modern machine learning algorithms.

5.0 OUTLOOK

Previously, we have presented a framework for dynamic multi-agent combat mission simulation. Vital aspects of such a simulation are not only a good architecture choice and adequate system modelling but also robust mission plans and behaviour models for those systems. Robustness is of major importance especially in a rapid prototyping environment where all models have to cope with changing system properties or completely new systems on own and enemy side. Our approach with separated high-level planning and low-level manoeuvre control as presented in section 3.3 has been proven to work with missions of different scope and complexity. With experienced operators and enough time, it is possible to create a consistent mission plan that is also robust to some extent to deviations due to unforeseen events. A problem in the context of simulation however is that it is often used by analysts and engineers only, thus no operators are available to provide their expertise in combat mission planning. It is therefore desirable to fully automate the process of mission planning including e.g. multiple subsequent coordinated attacks in many-to-many engagements with optimized assignments of weapons and targets. The general problem of multi-agent mission planning is not specific to our simulation, but applies to a wide range of simulations and unmanned systems in general.

A mission plan can most easily be described by “who will when be where to do what?” This applies to almost all missions independently of being carried out with manned platforms or UAVs, with one or many participants, in the real world or in simulation. As already pointed out, plans have to be robust against unforeseen events. Such events can be handled by reactive low-level agent behaviour, but they often require adaptations to the original mission plan. In easy cases, it is possible to realign the plan after a disturbance by simply tasking all agents to wait for the slowest agent (given they still have enough fuel). As this exposes the waiting agents unnecessarily to enemy threats, it is usually desired to find a better solution by changing the original mission plan. There are also situations where adapting the original plan is not only desired but necessary, e.g. when own platforms get shot down before achieving their mission goals. Adapting the plan, i.e. online re-planning for multiple coordinated assets, requires different techniques than purely reactive agent behaviour and is a challenging research task.

First off, the task is highly complex and the search space for the planning algorithm is accordingly huge. Recalling the description of a mission plan from the previous paragraph, it is composed of a set of usually heterogeneous agents, a set of possible actions that can be performed anywhere in a continuous 3D space and on a set of different targets. Many actions require cooperation of multiple agents and the outcome of those actions is often highly dependent on where it is carried out and on the world state when it is carried out. Additionally, the world is dynamic, partially unknown and can be explored and altered by the agents over time. Depending on the modelled depth, cooperation between agents can be hindered by limited to partially no communication. As already mentioned, it is not only desired to find a feasible plan but also to optimize it with respect to a desired cost function, e.g. minimize total mission time to reduce exposition to enemy threats. A more complex cost function could in turn try to maximize the probability of mission success, measured e.g. by the threat level of the entities, the number of munition available for the primary targets etc. The optimization problem has both logical and kinodynamic constraints, e.g. rules of engagement and the vehicles’ motion models. Given the complexity of the problem, it is in practice not possible to obtain a globally optimal solution within a reasonable amount of time (especially in the context of online re-

planning). A common approach is therefore to split the multi-agent mission planning problem into subproblems and solve them in a top-down or iterative way. Those subproblems usually relate to the fields of task planning, task assignment, task scheduling and motion planning.

In practice, there are even more requirements to the planning algorithm regarding its HMI. It is desired that mission plans and tactics can be adapted based on a high-level language. This applies to the simulation context where analysts want to quickly alter the course of different simulation runs without changing the source code as well as to real world applications where pilots might want to adapt the behaviour of supporting unmanned assets to a changed tactical situation on-the-fly. It is crucial for the acceptance of unmanned assets operating close to the manned platforms that they can be commanded (almost) as flexible as a manned wingman via voice communication. Furthermore, the output of a planning algorithm has to be transparent and human-interpretable as well. As by now, artificial intelligence systems have superior performance in very specific tasks but often lack awareness of the higher context compared to humans. To at least partially compensate this issue, a mission planning algorithm should be able to present a set of alternatives to an operator, e.g. the fastest plan, the safest, etc.

To our knowledge, there is currently no practically usable mission planning system that fully considers all the above points. The multi-UAV mission planning problem is without doubt very challenging, but with the recently increased number of different projects towards human-machine teaming it will surely see significant advances over the next years. In this context, the FPL can be used to integrate promising research approaches and to estimate how they scale to environments of increased complexity.

6.0 SUMMARY

Unmanned systems supporting manned platforms in future air combat environments will have a possibly huge force multiplication effect. The task of conceptualizing those platforms and the required subsystems like cross-platform mission management systems becomes however increasingly complex. To deal with this complexity, the FPL serves as a versatile tool to assess the operational performance of new concepts in a holistic system-of-systems approach. We have presented the core component of the FPL, a dynamic multi-agent simulation that allows simulating complete combat missions in realistic future threat environments and how it was used to answer questions in the fields of technology identification, concept validation and system prototyping. Based on our experience from those tasks, we have outlined what might be one of the biggest future challenges not only for simulation but also for the introduction of unmanned systems in general: Implementing a robust high-level planning algorithm that generates ad-hoc mission plans for complex air operations while considering reactive low-level agent behaviour, human operators and online user input. As we are already working on solving this challenge, we expect the FPL to be further of use as efficient and realistic prototyping environment over the next years.

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Optimizing Flight Paths Through Anti-Aircraft Gun Fire with Machine Learning

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ABSTRACT

We present a methodology intended to optimize the flight path through a flight corridor occupied by enemy anti-aircraft guns. This is relevant for all kinds of aircraft, missiles, and drones moving through air space that is fully or partially controlled by such guns. To this end we use Q-learning - a type of reinforcement (machine) learning - which tries to find the optimal strategy to avoiding the anti-aircraft guns through repeated semi-random flight path trials. Q-learning can produce an optimal flight path through the enemy fire without modeling the anti-aircraft guns directly. An adversary response is still needed, but this can come from a black box simulation, user input, real data, or any other source. Here, we use an in-house tool for generating the anti-aircraft fire. This tool simulates a close-in weapons system (CIWS) guided by a fire control radar and Kalman flight path prediction filters. Q-learning can also be supplemented with neural networks - so-called deep Q-learning (DQN) - to handle even more complex problems. In this work, we present results for a subsonic flight corridor pass of one anti-aircraft gun position using classic Q-learning (no neural networks).

1.0 INTRODUCTION

Machine learning has been around for many years, but has seen a surge of interest in recent years due to major improvements in some applications; mainly image and speech recognition, and reinforcement learning. Speech recognition is used in cell phones and appliances, such as Apple's Siri or Amazon's Alexa, while image recognition is found in many places; such as surveillance, autonomous vehicles, medicine, and social media apps. Both speech and image recognition use deep neural networks trained specifically for each application [1]. Reinforcement learning is a more general form of machine learning, not restricted to images or sound [2]. The main principle of reinforcement learning is to set up a challenge, such as a game, with one or more agents (players) in an environment. The agents play a round of the game, and are subsequently rewarded by a judge (the environment) according to their performance. The agents then update their notebooks (aggregated reward tables) to remember (and later repeat) smart moves, or avoid bad ones. After a sufficient amount of games played, the agents will settle on any available optimal solutions. This works fine for simple problems, such as finding your way through a maze, but for more complex challenges, e.g. Go or Chess, the amount of possible states during a game often prohibits building any kind of table containing all states. This has limited meaningful applications of reinforcement learning for many years. However, recently researchers have started using neural networks to replace these state tables. The rewards gained during the game are used to train a neural network to recognize smart moves or patterns, instead of building a state table. These networks can provide good approximations to the state tables, at fractions of the size. A company called Deepmind (acquired by Google) has had great success with this approach in training agents to play Atari games, Go, and Chess [3–7]. Their success has spawned a new interest in reinforcement learning. It has, however, turned out to be difficult to use reinforcement learning in more complex, real life situations, so practical applications of reinforcement learning are still rare.

In this paper we use a form of reinforcement learning called Q-learning to simulate an object (missile, drone, etc.) flying towards a target located next to an anti-aircraft gun. The adversaries in the game are the defending anti-aircraft gun and the incoming flying object, which is rewarded for avoiding the anti-aircraft gun's bullets. The flying object is the only learning agent in the game. The anti-aircraft gun is part of the environment, hence will not improve its performance over time. Furthermore, the flying object is initially flying in a straight line with a fixed speed towards the target, before learning to deviate from the straight path to avoid the anti-aircraft gun's bullets. The anti-aircraft gun is simulated by in-house software taking into account fire control radar properties, ballistics, and flight path predictions. The purpose of the game is to find the flight path with the optimal survivability for the incoming flying object.

Earlier studies done with reinforcement learning on flying objects include homing-phase missile guidance law design [8], and obstacle avoidance for UAV's [9]. Our group has also used deep reinforcement learning for battlefield strategy planning [10].

2.0 Q-LEARNING

The core of Q-learning is to define a problem, set up a table containing all possible states of the problem (the so-called Q-table), and calculate values of the quality of all available actions at these states through simulations [2]. A well-formed problem will converge on a local or global optimal solution, illustrated in Figure 1. Furthermore, the Q-table can be replaced by a neural network to create a deep Q-learning network (DQN). We have chosen to simplify matters initially by not using a neural network. This traditional Q-learning approach has been satisfactory for the problem presented here, but it might be insufficient for more complex cases.

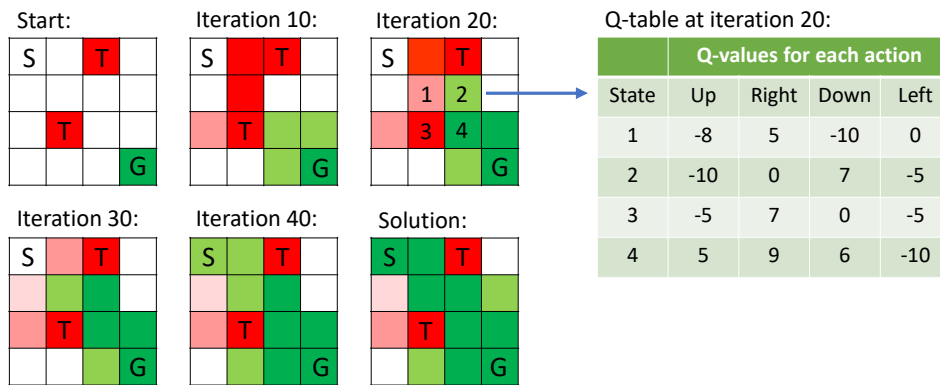


Figure 1: Illustration of a simple grid problem solved by Q-learning. The top left grid shows the starting layout with the starting point (S), the green goal (G), and two red traps (T) to be avoided, while the bottom right grid shows the optimal path from S to G reached by Q-learning. The Q-learning process tries many random paths from the starting point, and registers the success of potential future moves (Q-values) in each square (state). Green indicates positive Q-values, while red shows negative Q-values. The optimal solution is built over many iterations, four of which are shown here. The table of all Q-values in all states is called the Q-table. Part of the Q-table at iteration 20 is shown on the right.

Every iteration of the actual Q-learning process starts by updating the current flight path, which is done by either picking the best Q-value from the Q-table, or choosing a random direction, at every step along the flight path. This is called exploitation vs. exploration, and the frequency of random exploratory steps is called the exploration rate (set to 0.3 here) [11]. After updating the flight path, rewards are calculated along the current track by feeding it into the anti-aircraft gun simulation, which simulates the full encounter and returns a list of minimum separations between the fired bullets and the incoming flying object, along the

track. These separations are converted into rewards, larger separations giving higher rewards, which are then used to update the Q-table along the current track;

$$Q^{\text{new}}(s_t, a_t) = (1 - \alpha) \times Q^{\text{old}}(s_t, a_t) + \alpha \times (r_t + \gamma \times \max Q(s_{t+1}, a))$$

where α is the learning rate, r_t is the reward received when going from state s_t to state s_{t+1} , a_t is the action taken, and γ is the discount factor. The learning rate (set to 0.1 here) determines to what extent newly acquired information overrides old information. A factor of 0 makes the agent learn nothing, while a factor of 1 makes the agent discard all prior knowledge. The discount factor (set to 0.99 here) determines the importance of future rewards. A factor of 0 will only consider the current reward (r_t), while a higher factor also will include long-term rewards. $\max Q(s_{t+1}, a)$ is the highest Q-value of all possible actions at state s_{t+1} . Only the states and actions visited by the current track are updated. For a complex problem with a large Q-table, it often takes millions of runs to build a complete Q-table.

3.0 LAYOUT

Reinforcement learning is a process with one or more agents trying to maneuver through an environment in an optimal way. The environment reacts to the agent(s), giving negative or positive feedback (rewards) along the way. In this paper the environment consists of an anti-aircraft gun with a target next to it. The gun is simulated by a program written at FFI which takes many factors into account, such as; the fire control radar, bullet ballistics, and flight path prediction. The mechanical properties of the gun, e.g. maximum horizontal and vertical turning speed, are also considered. The flight path prediction is handled by a Kalman filter, and the gun is set up as a typical 30 mm Close-In Weapons System (CIWS) with an effective range of 3 km. It fires constantly at the incoming object, starting before the object comes within range to take bullet travel time into account. The gun, and target, are located 10 m above the ground, with a 30 m separation, shown in Figure 2.

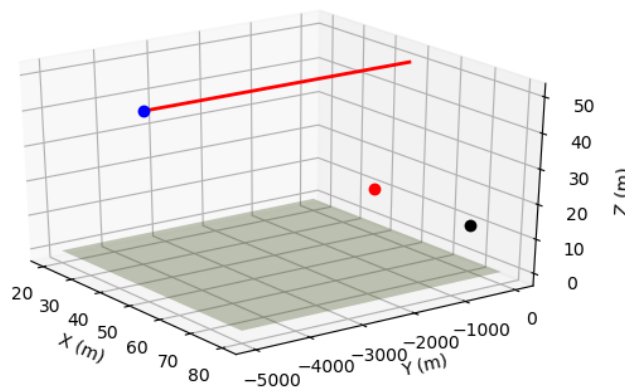


Figure 2: The layout of the simulation, with the blue dot showing the starting point of the flying object 50 m above the ground, 5 km from the target (red dot) and anti-aircraft gun (black dot). The starting point is at X = 50 m, the target is at X = 40 m, and the gun is at X = 70 m. Both the target and gun are located 10 m above the ground. The red line shows the initial flight path (right and into the paper) before alterations by the reinforcement learning process. Note the different scale on the Y-axis.

4.0 Q-TABLE SETUP

To allow the use of a classic Q-learning approach (no neural networks), it is adamant to limit the size of the Q-table. If it does not fit within the computer memory, updating and accessing it becomes prohibitively slow. To achieve this, the flight path is intersected by grids at 25 m intervals, giving 200 intersections for the

whole 5 km track. Moreover, these grids are divided into 51 vertical and 51 horizontal bins (25 on each side of the central bin), i.e. 2601 bins in each grid. Each bin is 2 m x 2 m, giving a total grid coverage of 102 m x 102 m. Multiplying 2601 bins by 200 grids produces 520 200 bins (states) in total for the Q-table. Furthermore, the flying object can choose between nine actions at every state (bin) when moving to the next intersection; straight forward, up, up to the right, right, down to the right, down, down to the left, left, and finally, up to the left, shown in Figure 3. This gives every state nine Q-values, i.e. 4 681 800 Q-values for the whole Q-table, well within the capacity of most computers.

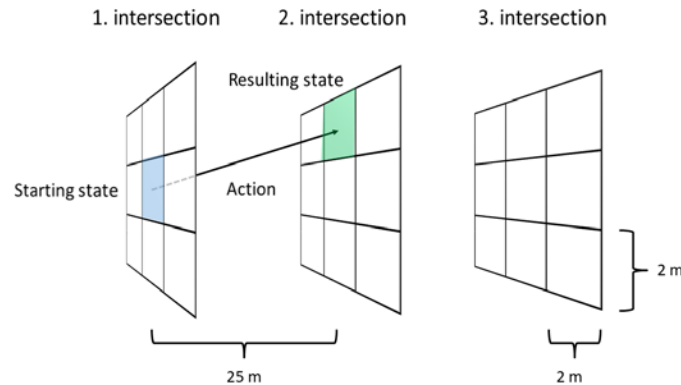


Figure 3: The first three intersections out of 200. Each intersection contains 51 x 51 states (3 x 3 in the figure), with each state having nine possible actions and resulting states in the following intersection. Intersections are 25 m apart, and each bin (state) is 2 x 2 m.

3.1 Rewards

The rewards are calculated by taking the logarithm of the minimum separation between the anti-aircraft bullets and the flying object divided by 10 (limited to the range 1–100 m), which produces rewards ranging from -1 (1 m separation) to 1 (100 m separation). The zero point is at 10 m separation. This keeps the average reward close to zero (avoiding divergence in the Q-values), and reduces the gradient of the rewards at large separations where the benefit of increasing the separation is negligible. The reward for reaching the target is fixed at 500.

5.0 RESULTS AND CONCLUSION

Figure 4 shows the Q-values after 500 000 simulations. Q-values below three are excluded from the plot to make it less cluttered. The black smoothed line shows the optimal track (maximum Q-values) from start to finish. It spirals towards the target (with a 10 m radius) after coming within the 3 km range of the anti-aircraft gun. Running further simulations does not change the flight pattern significantly, indicating that this is a local or global optimal flight path for avoiding this particular anti-aircraft gun and flight path predictor.

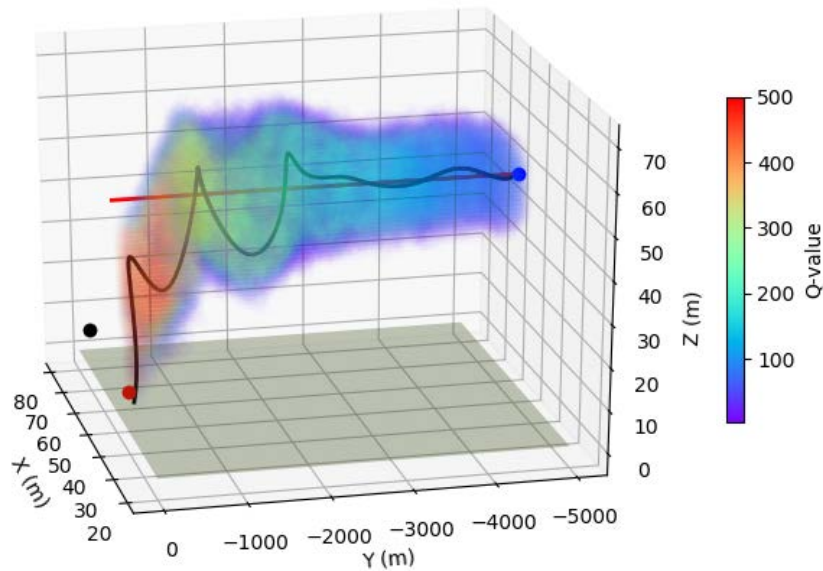


Figure 4: Q-values and optimal track (black line) after 500 000 simulations. The flight starts at $Y=-5000$ m (blue dot), and ends at the target ($Y=0$, red dot). The black dot shows the anti-aircraft gun position (30 m from the target), and the red line shows the initial track.

The original and optimal tracks from the simulations, shown in Figure 4, are presented in greater detail from four different angles in Figure 5, with the spiralling pattern clearly visible.

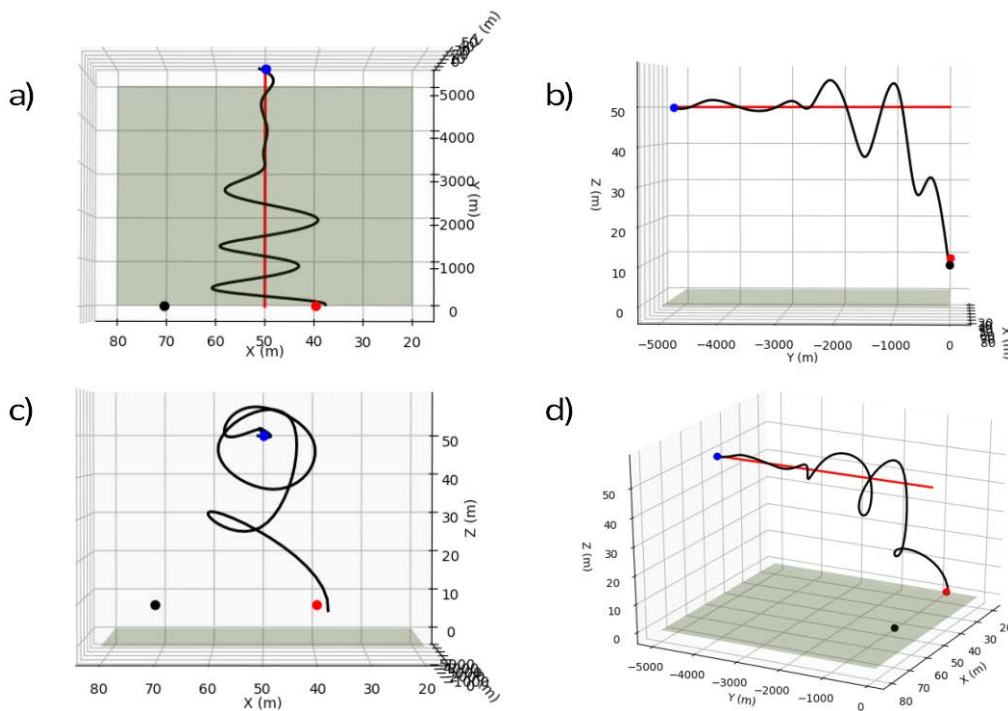


Figure 5: The optimal track (black) after 500 000 simulations from four different angles; a) top looking down, b) side view, c) front view, and d) side/front view. The blue dot shows the starting position, the red dot is the target, the black dot indicates the position of the anti-aircraft gun, and the red line shows the initial straight flight path.

To conclude this paper; by setting up a well-formed and simplified problem, nontrivial solutions to the optimal flight paths through anti-aircraft gun fire can be reached by classic Q-learning without using neural networks, due to the extensive computing power and memory storage of modern PC's.

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Intelligence Tools for Environmental Threats: Integrated Technologies for Chemical Hazards

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ABSTRACT

Accounting for environmental hazards in mission planning requires the most up-to-date observations and forecasting of the dynamic battlefield environment. In addition, some hazards, such as the exposure to toxic industrial chemicals and materials (TIC/Ms) in complex urban environments, cannot be predicted in time and space without significant a priori knowledge of TIC/Ms presence in the battlefield, potential release scenarios, and the dynamic ongoing natural environmental processes that result in hazardous soil, water, and air exposures. Teams at the US Army Engineer Research and Development Center (ERDC) are engaged in the development of tools to improve the timeliness and reduce the uncertainty of TIC/Ms risk identification through the integration of spatial and database tools including probable TIC/M locations and quantities, toxicological hazards, fate and transport properties, and soil properties. Furthermore, ongoing efforts to expand the reach of operational hydro-meteorological prediction allow these tools to be applied in rapid fate and transport modelling with greater certainty over a larger swath of the globe than is presently possible. The end result will enable more accurate and dynamic understanding of the chemical hazard potentials that can be encountered during battlefield operations, allowing for better informed routing and equipment selection.

1.0 INTRODUCTION

The presence of toxic industrial chemicals and toxic industrial materials (TIC/Ms) in contested areas creates a challenge for accurately assessing and planning for Warfighters' exposure risks. Chemical hazards encountered during operations may come from a variety of sources, including purposeful releases of a predictable scale such as chemical and biological weapon strikes, purposeful releases of improvised chemical weapons, or purposeful and accidental releases of chemical materials stored or transported in and around areas of operation. Therefore, Warfighters generally lack the understanding of potential lethal environments that may be encountered during active engagement and predictions of how to operate in, avoid, or prepare for exposure during sustained operations.

1.1 Need for this capability

There are several existing utilities, tools, and models used to inform planning practices on chemical hazards and risks. This includes several web-based software applications such as the Joint Acquisition CBRN Knowledge System (JACKS), Joint Warning and Reporting Network (JWARN) the early warning system, and the Joint Effects Model (JEM) and CBRN-Information Systems (CBRN-IS) that report hazards and suspected impacts. These programs rely on a number of individual media modelling capabilities including HPAC for aerial dispersion modelling, Incident Command for Drinking Water Protection (ICWater) and Specialized Hazard Assessment Response Capability (SHARC) for waterborne hazard modelling, and others. The US Army needs

intelligence tools that will predict, quantify, and plan for TIC/M potential threat and these tools need to enable a near real-time dynamic ability to identify and assess chemical threats.

1.2 Integrated project objectives

This effort seeks to improve mission planning and situational awareness by predicting TIC/M threats on timescales relevant for mission planning through integrated chemical hazard modelling. This solution must include:

- Mechanistic, quantitative models for rapid chemical environment evaluation and intuitive impact assessments to support mission planning, situational awareness, and mission success
- Knowledge of industries' potential chemicals, including transport profiles, interaction and degradation (air, water, soil) in dynamic operating environments
- Breakdown products of chemical agents of opportunity

2.0 SURVEILLANCE OF TIC/MS

2.1 TIC/Ms Surveillance gap

Due to the vast diversity of TIC/Ms, the US Army relies on multiple databases of chemical information as TIC/M resources during mission planning. These databases, for example those used in the JEM program, are extensive, but are not complete of all TIC/Ms, some of which present a significant exposure risk to the Warfighter. Additionally, the JEM program does not include the potential threats due to chemical breakdown products created in the environment after release, and the complete chemical properties for many breakdown products are not present in chemical property databases. Thus there is need to create tools that can identify and quantify TIC/Ms and their breakdown products based on identified industries.

2.2 TIC/M Intelligence database solution

The TICM-DB tool (Figure 1) is designed to field a variety of potential queries such as TIC/Ms associated with particular industries, potential TIC/Ms from illicit activities, and additional chemical breakdown products potentially resulting from deliberate fires and collateral damages. As shown in Figure 1, this is achieved by bringing together multiple sources of information.

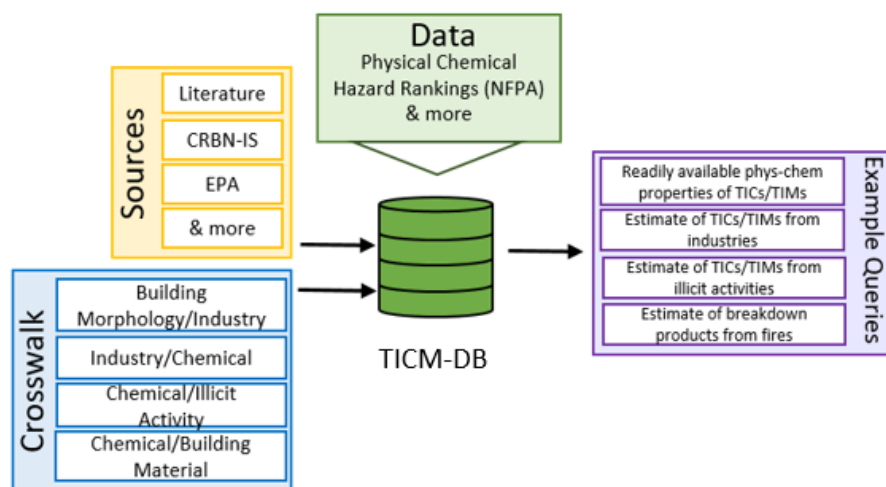


Figure 1, TICM-DB product

The ability to estimate the presence of TIC/M compounds in urban and industrial battlefields is necessary to identify potential sources of chemical hazards. A survey of the US Environmental Protection Agency (EPA) Toxic Release Inventory (TRI) has previously been used to develop relationships between particular industries with the types of chemicals that are used in those industries [1]. The TRI reports on annual releases from industrial and civic chemical use sites such as those operated in the manufacturing, service, and transportation industries. While the TRI gives detailed information about activities within the US, the relationships between certain industries and certain chemicals are broadly applicable. Further development of this capability is based on the hypothesis that most industrial sites throughout the world are based on US, European, Russian, Japanese, Korean, or Chinese design allowing the development of a library of industries based on site morphology. When combined with the identification of an area of interest (AOI) from socio-political mapping sources and other data, the relationships between industries and chemicals become a powerful TIC/Industry crosswalk capability (Figure 2) for estimating the potential for chemical threats where ground level intel is sparse.

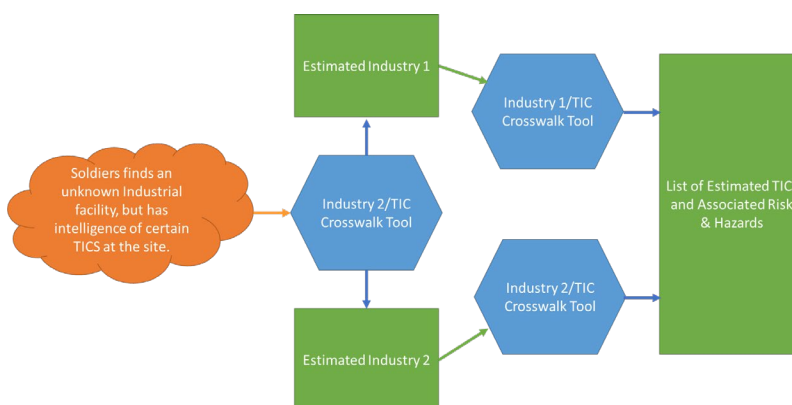


Figure 2, TIC/Industry crosswalk tool to develop chemical site risk information from limited knowledge

The TICM-DB tools also incorporate unconventional sources of TIC/M related hazards. Chemicals not traditionally identified with weaponry may also present incidental release or improvised weapons hazards due to their chemical and toxicological properties. Other materials in the contested environment such as building materials may release hazardous compounds if burned. Illicit drug manufacturing and processing activities constitute an industrial activity outside the purview of the TRI. Web scraping techniques are being utilized to develop data sets of observable and quantifiable georeferenced information to serve as the basis of relationships that predict the type and quantity of unconventional materials in AOIs. TICM-DB is also being designed for flexible expansion to include other hazardous materials that are not considered TICs such as radioisotopes, flammable, and reactive materials.

A second critical component, the quantities of TIC/Ms in an AOI, is needed for any estimate of the potential exposure. Cross walking the presence of industries and the associated chemicals that may be present with the chemical volume or masses needed to support production levels establishes de minimus TIC/Ms quantities in the AOI. Further refinement is enabled by site specific morphology such as visible presence or absence of storage tanks, observed production rates, reported profits, and other financial information. Real-time updating can be informed by observations of delivery, product, and waste transportation.

3.0 CHEMICAL PROPERTIES

3.1 Chemical property need

Even for known weaponized and improvised chemical threats, the physical chemical properties aspects of the current databases are incomplete. This is partially due to the vast nature of possible chemicals that may be encountered, the lag in testing to establish new materials, and the limited requirements in many countries for required reporting of proprietary formulations.

3.2 Chemical property solution

Working on the hypothesis that better quality TIC/M data is achievable, missing properties are being identified and values provided by multiple methods. Some of the desired data for all chemical species of interest are density, viscosity, solubility, pKa, Henry's law constant, vapor pressure, free energy of solvation, boiling point, flash point, partitioning coefficients (K_{ow} , $K_{heptane-water}$, K_{oc}), Micelle/membrane interactions, degradation kinetics, and potential impact on soldiers, which might be detrimental to potential operations in the contested environment. Efficient computational algorithms (Figure 3) are used for the gap analysis of existing property data in which data is sourced from existing databases, literature, and web sites and gaps are identified and tabulated. The algorithm examines the range of parameter values and the dependency of chemical property parameters on other variable parameters as an assessment of existing chemical property data quality and uncertainty.

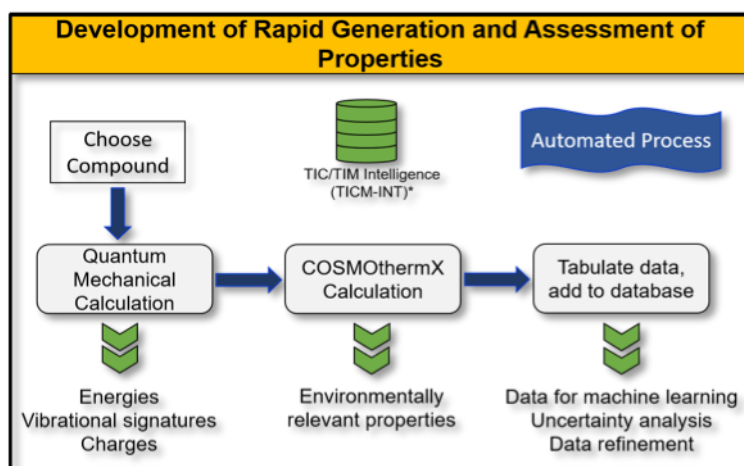


Figure 3, Automated process for the completion of TIC/M database information.

Computational chemistry allows the synthetic generation of chemical property data based on quantum-chemical first principles in a statistical thermodynamic framework. The obtained values will be compared with the data obtained at other computational levels such as by Estimation Program Interface v4.11 (EPI Suite™), which is a QSAR based predictive package distributed by US EPA and, for those compounds with identified experimental values, compared against measured values. Those data with significant disagreement will be further analysed and will be computed using more rigorous calculations using ab initio and molecular dynamics simulation approaches and thus uncertainty in the data will be minimized. For those compounds with incomplete experimental data sets and for new compounds without experimental data the computational method provides predictive capabilities to fill the gaps in the chemical property database thereby improving and expanding the capability to predict exposure risk to the Warfighter. The resulting chemical property database for the fate, transport, and effects of compounds in complex media will be linked to a database of degradation kinetics for compounds in the natural environment.

3.2.1 Chemical reactivity mapping

There is no product currently available in the field that rapidly predicts exposure risk due to the chemical products of reaction and degradation in the environment. That capability first requires the prediction of viable reaction pathways. A recently developed semi-empirical method computationally generates multistep chemical reaction pathways from the very first step (reagents) to final product including intermediate and speed limited steps. Kinetic parameters are computed from Gibbs free energy changes over a range of temperatures. The speed of reagent decay and product formation can be predicted along with half-lives of key components using the computed kinetic parameters. Reaction kinetics with selected reactive species available in natural surroundings as well as bulk water will also be evaluated for selected compounds.

3.2.2 Phase partitioning

Phase partitioning properties are necessary to assess TIC/M transport in the complex multimedia environment. Of particular concern are mass partitioning from liquid phase release to gas phase and liquid or gas phase release to solid surfaces. In the first case this is because chemicals in the gas phase typically migrate more rapidly from the release point and in the latter case it is because some chemicals may present a long lasting residual exposure hazard in surface soils and the built environment. Electronic structure calculations are planned to compute

several partitioning coefficients such as K_{ow} , $K_{heptane-water}$, K_{oc} , Micelle/membrane interactions using the Gaussian 09, Turbomol, and COSMOmic software packages. Select properties will also be computed using traditional density functional theory and molecular dynamics simulation approaches.

3.2.3 Data analysis/quality assurance

Computational algorithms will be developed to expedite computational data generation using various computational chemistry methods for efficient data analysis and uncertainty reduction among the data already available from the literature. Calculation of correlation coefficients will help to understand the prediction reliability of computational data as well as the quality of the experimental data. Data with greater uncertainty will undergo further analysis and more rigorous calculation to refine the predicted physical and chemical properties. These methods also allow the generation of temperature dependent properties which facilitates high fidelity fate and transport modelling across a wider range of local conditions.

4.0 FATE AND TRANSPORT

4.1 Dynamic Fate and Transport need

Warfighters interacting with water bodies during and after TIC/M release events need actionable information about contaminant exposure risk. Chemicals released to water bodies result in spatially and temporally dynamic concentrations that expand and flow downstream over time. In addition, contaminants are frequently present even when they are not visible and may create a secondary hazard by volatilizing to the air around the stream both of which increase the risk in using in-situ visual inspection as a mechanism to assess exposure potential.

4.2 Fate and transport solution

Georeferenced modelling tools can rapidly identify TIC/M exposure risk in an actionable format. The desired product informs on the extent of chemical spread and the severity of the contamination in terms of hazard risk in a time dynamic presentation. The development of a singular site model for a defined temporal period is not a novel capability but expansion to a non-site specified and dynamic utility that can be applied to multiple sites without knowledge of the chemical compounds a priori requires additional inputs as automated data streams rather than user formatted files (Figure 4).

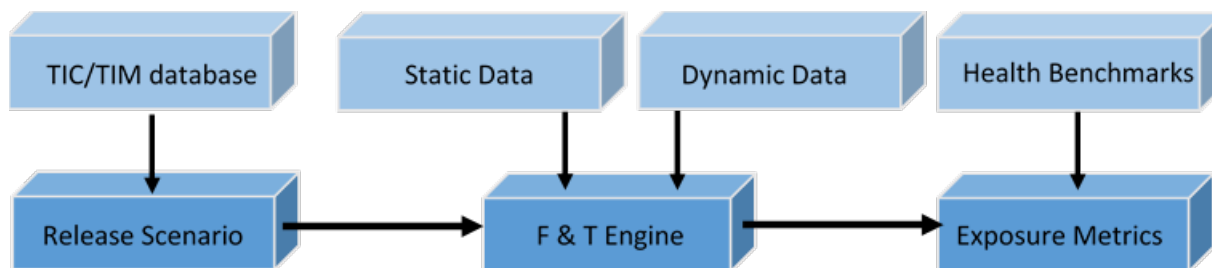


Figure 4, Essential components of the ITCH model system to predict dynamic human exposure

4.4.1 Release scenarios designed for minimal user input

The TICM-INT tools being developed to identify potential sources and quantities of chemicals within a contested AOI are critical for determining potential concentrations in surface water due to chemical releases. Similarly, much of the static description of the AOI can be extracted from georeferenced datasets such as

drainage areas, infrastructure and stream channel locations, and soil types (as informed by the pedoinformatic approach described previously). But, for dynamic modelling, the rate of release is also a critical component. The models for rapid surface water concentration currently available require extensive user input to characterize chemical sources, failure, and release mechanisms because the rate that mass enters the environment to initiate exposure is calculated from detailed physics based scenarios. In the ITCH fate and transport system a guided decision tree approach is being developed that incorporates key information about the range of parameters used for the detailed physics based scenarios. In addition, the system will identify greatest risk scenarios that assume the maximum release rate anticipated for a given type and volume of storage to provide users an upper limit of exposure as well as an expected value or chemical concentration.

4.2.2 Dynamic system of data and models

A second key component of our approach is the inclusion of near real-time and forecasted dynamic data to describe the hydro-meteorological conditions of the AOI. Although average annual properties such as temperature, precipitation, streamflow, wind speed, and wind direction can be used to produce acceptable estimates of the long term average expected behaviour of a system, that is not sufficient to predict the potential exposure for a specific ongoing or near future activity due to the high variability of the hydro-meteorological parameters. Authoritative global meteorological data is linked to ERDC's Streamflow Prediction Tool which performs hydrologic and mass routing. An uncoupled one dimensional advection dispersion model moves the chemical hazard downstream, allowing it to spread over time resulting in concentration time series for each stream reach in the AOI. The advection dispersion model also adjusts the quantity of contaminant in the water column based on solid sorption in the water column and to sediment, partitioning to the gas phase, and degradation kinetics.

4.2.3 Visual Display of Actionable Information

Figure 5 demonstrates the anticipated surface water chemical hazard mapping product. Figure 5(a) shows the concentration time series at a single stream segment location informed by the chemical release scenario, dynamic hydrologic routing, fate determining processes. Comparison between the modelled concentrations and benchmark health effect screening concentrations results in an assignment of risk levels. Figure 5(b) shows the result of multiple stream reach concentration and benchmark comparisons for single time. This type of output could be used to determine gap crossing locations with reduced exposure risk.

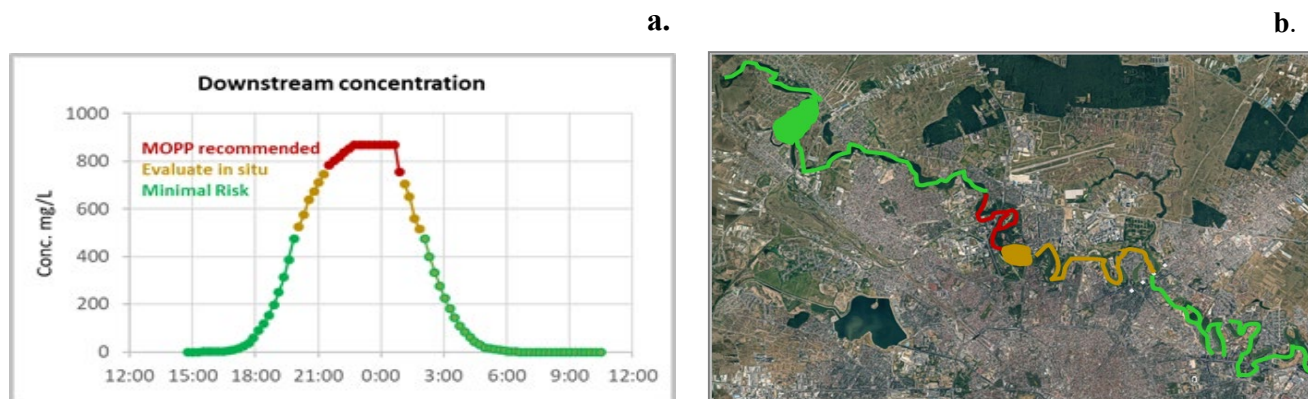


Figure 5, actionable display of chemical hazard in stream

5.0 SOILS

5.1 Soil need

There is a high likeliness that Warfighters will interact with contaminated soils during and after a TIC/M event that is not accounted for in mission planning. Furthermore, exposure via soil contact is not currently modelled as a dynamic source of risk to the Warfighter. But of all the media, soil can be transported with the Warfighter and has the capability to lead to longer exposure durations and therefore higher risk. This can result in significant negative consequences for mission success. The complexity of soils represents a formidable technology barrier in predicting contaminant environmental fate. Complexity arises from the fact that soils are both chemically and physically heterogeneous multiphase materials that respond dynamically to the biological and hydro-meteorological surroundings while reflecting the geologic history of their locale. In addition, human activities can change the chemical and physical behaviour of soils, directly impacting contaminant fate. Urban soils, and those taxonomically identified as anthrosols and/or technosols, are unique and complex materials that can be considered physically and chemically disturbed from their pristine state. The fate and transport of chemical hazards to groundwater, surface water, and the atmosphere in contested urban environments depends on accurate characterization and mapping of urban soils and their expected properties.

5.2 Soil solution

Increased mission readiness and situational awareness can be enabled by understanding TIC/Ms fate and transport in soils, including urban soils. Thus there is a need to identify, classify, and characterize urban soils with similar geomorphological factors globally, and quantify sorption/degradation parameters in these urban soils of selected TIC/Ms.

5.2.1 Development of urban soil analogs

A field collection protocol [2] that is applicable to urban soils will be applied to collect samples at location analogs for AOIs outside the United States. In the urban environment, ongoing soil formation processes combined with the pre-existing pristine soil properties create the unique properties of the anthrosol. Features such as abrupt and clear depositional boundaries, specific and strong chemical features (i.e. stark pH or mineralogy contrast), altered physical features, specific biologic (flora and/or fauna) communities, early stage pedogenesis, or synlithogenesis are specific soil forming factors that can be used to classify an anthrosol. The selection of analog sites is non-trivial requiring the application of a pedoinformatic approach that accounts for factors such as USDA-NRCS and/or WRB classification, parent material, climate, landscape position, and vegetation. Field collections extend to a depth of 24" from the soil surface. A thorough physico-chemical characterization generates base data for a multivariate geo-statistical analysis to determine which of the soil physicochemical factors are tied to chemical fate.

5.2.2 Experimental sorption/degradation of TIC/Ms in urban soils

Multiple processes affect the fate and transport of hazardous chemicals in urban soils including sorption, degradation, and surface complexation. As urban soils are characterized a selection of representative surfaces will be selected for additional studies utilizing microcosm and breakthrough column approaches to evaluate the role of urban soil constituents on chemical retention and the ultimate potential for chemical exposure. Soil constituent factors such as silicates, carbonates, metal oxides, and organic material are likely to be important factors. Soil specific chemical parameters established through batch isotherm and kinetic studies will also serve

as validation experiments for the previously described computational prediction of sorption and reaction parameters.

5.2.3 Digital soil mapping

Chemical and physical soil heterogeneity leads to a heterogeneous fate and transport behaviour in the environment. To utilize the chemical fate parameters determined for urban soils there needs to be a georeferenced capability to identify the soil in the AOI, the heterogeneity of that soil, and the associated physical chemical properties to apply. Digital map layers will enable the linkage between location and appropriate properties which in turn informs which fate determining processes are significant at a given site. This reduces the burden to individually generate fate and transport models for specific locations and increases the fidelity of the model to the range of observed or modelled system properties. The result is an improved prediction of the potential for exposure via soil transference in contested areas.

6.0 PLANNED INTEROPERABILITY WITH OTHER CAPABILITIES

6.1 USACE DRiVE package

Course forecasting, navigation, and routing tools need to account for the fixed physical environment as well as short term changes in conditions. These conditions can include traffic, weather, road hazards, human movement, and other difficult to predict influences on the safety and suitability of a particular course. A real-time analysis of the visual field can provide moment-by-moment information on some of the dynamic conditions, but no tools are currently available that manage exposure risks from the chemical hazards present in contested environments. Given that exposure pathways along soldier routes present a risk for adverse effects that may include physical and/or mental impairment, there is need for a product that can proactively manage exposure risk by assessing the potential for exposure and presenting alternative routing options.

6.2 Drive overview solution

ERDC is developing routing tools that incorporate the products described for the ITCH project above in the DRiVE package. The DRiVE project also incorporates airborne chemical hazards generated from a separate modelling effort but dependent on the same TICM-DB databases and computationally derived chemical properties as the ITCH project. A Toxicological Operational Knowledgebase System (TOKS) is planned to expand on the TICM-DB database with biological effects of TIC/Ms and conventional chemical, biological, radiological and nuclear threats. Multiple acute inhalation toxicity reference values will be leveraged to develop probabilistic assessments of risk. Routing decisions in DRiVE utilize probabilistic risk and cost function game theory rather than shortest travel distance or travel duration to choose acceptable routes. Thus, risk due to multiple sources can be accommodated in route selection.

7.0 CONCLUSIONS

7.1 Implications of this work

Future mission planners will have increased capability through the ITCH tools to assess potential lethal environments that may be encountered during active engagement. Sparse ground level data on the location and quantity of TIC/Ms in the urban environment will no longer limit the ability accurately assess chemical hazard exposure risks. Utilizing advanced computational methods to determine the properties that govern the fate of

chemicals in the environment, higher fidelity modelling will be available for a comprehensive list of chemicals and chemical breakdown products. With near real-time capability to ingest and process hydro-meteorological conditions and the ability to predict soil properties in urban environments the dynamic fate and transport of TIC/Ms in surface water and soils will also be predictable. This will reduce the risk of impaired soldier functions or mortality due to unplanned exposures and increase tactical advantages during operation and sustainment in contested urban environments.

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2.0 SURVEILLANCE OF TIC/MS

2.1 TIC/Ms Surveillance gap

Due to the vast diversity of TIC/Ms, the US Army relies on multiple databases of chemical information as TIC/M resources during mission planning. These databases, for example those used in the JEM program, are extensive, but are not complete of all TIC/Ms, some of which present a significant exposure risk to the Warfighter. Additionally, the JEM program does not include the potential threats due to chemical breakdown products created in the environment after release, and the complete chemical properties for many breakdown products are not present in chemical property databases. Thus there is need to create tools that can identify and quantify TIC/Ms and their breakdown products based on identified industries.

2.2 TIC/M Intelligence database solution

The TICM-DB tool (Figure 1) is designed to field a variety of potential queries such as TIC/Ms associated with particular industries, potential TIC/Ms from illicit activities, and additional chemical breakdown products potentially resulting from deliberate fires and collateral damages. As shown in Figure 1, this is achieved by bringing together multiple sources of information.

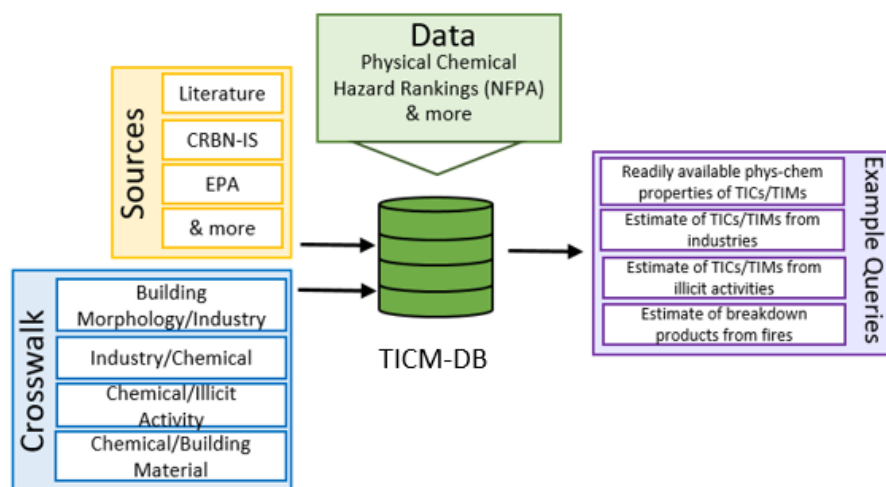


Figure 1, TICM-DB product

The ability to estimate the presence of TIC/M compounds in urban and industrial battlefields is necessary to identify potential sources of chemical hazards. A survey of the US Environmental Protection Agency (EPA) Toxic Release Inventory (TRI) has previously been used to develop relationships between particular industries with the types of chemicals that are used in those industries [1]. The TRI reports on annual releases from industrial and civic chemical use sites such as those operated in the manufacturing, service, and transportation industries. While the TRI gives detailed information about activities within the US, the relationships between certain industries and certain chemicals are broadly applicable. Further development of this capability is based on the hypothesis that most industrial sites throughout the world are based on US, European, Russian, Japanese, Korean, or Chinese design allowing the development of a library of industries based on site morphology. When combined with the identification of an area of interest (AOI) from socio-political mapping sources and other data, the relationships between industries and chemicals become a powerful TIC/Industry crosswalk capability (Figure 2) for estimating the potential for chemical threats where ground level intel is sparse.

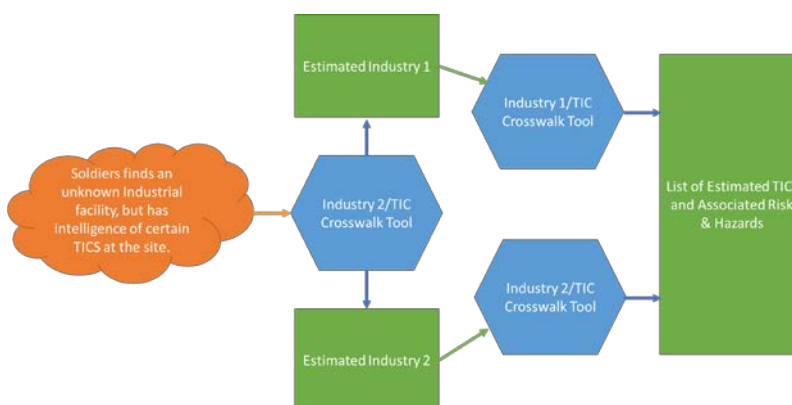


Figure 2, TIC/Industry crosswalk tool to develop chemical site risk information from limited knowledge

The TICM-DB tools also incorporate unconventional sources of TIC/M related hazards. Chemicals not traditionally identified with weaponry may also present incidental release or improvised weapons hazards due to their chemical and toxicological properties. Other materials in the contested environment such as building materials may release hazardous compounds if burned. Illicit drug manufacturing and processing activities constitute an industrial activity outside the purview of the TRI. Web scraping techniques are being utilized to develop data sets of observable and quantifiable georeferenced information to serve as the basis of relationships that predict the type and quantity of unconventional materials in AOIs. TICM-DB is also being designed for flexible expansion to include other hazardous materials that are not considered TICs such as radioisotopes, flammable, and reactive materials.

A second critical component, the quantities of TIC/Ms in an AOI, is needed for any estimate of the potential exposure. Cross walking the presence of industries and the associated chemicals that may be present with the chemical volume or masses needed to support production levels establishes de minimus TIC/Ms quantities in the AOI. Further refinement is enabled by site specific morphology such as visible presence or absence of storage tanks, observed production rates, reported profits, and other financial information. Real-time updating can be informed by observations of delivery, product, and waste transportation.

3.0 CHEMICAL PROPERTIES

3.1 Chemical property need

Even for known weaponized and improvised chemical threats, the physical chemical properties aspects of the current databases are incomplete. This is partially due to the vast nature of possible chemicals that may be encountered, the lag in testing to establish new materials, and the limited requirements in many countries for required reporting of proprietary formulations.

3.2 Chemical property solution

Working on the hypothesis that better quality TIC/M data is achievable, missing properties are being identified and values provided by multiple methods. Some of the desired data for all chemical species of interest are density, viscosity, solubility, pKa, Henry's law constant, vapor pressure, free energy of solvation, boiling point, flash point, partitioning coefficients (K_{ow} , $K_{heptane-water}$, K_{oc}), Micelle/membrane interactions, degradation kinetics, and potential impact on soldiers, which might be detrimental to potential operations in the contested environment. Efficient computational algorithms (Figure 3) are used for the gap analysis of existing property data in which data is sourced from existing databases, literature, and web sites and gaps are identified and tabulated. The algorithm examines the range of parameter values and the dependency of chemical property parameters on other variable parameters as an assessment of existing chemical property data quality and uncertainty.

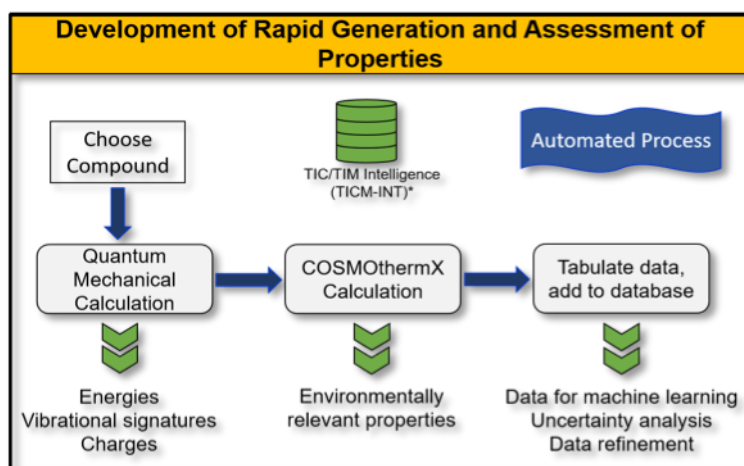


Figure 3, Automated process for the completion of TIC/M database information.

Computational chemistry allows the synthetic generation of chemical property data based on quantum-chemical first principles in a statistical thermodynamic framework. The obtained values will be compared with the data obtained at other computational levels such as by Estimation Program Interface v4.11 (EPI Suite™), which is a QSAR based predictive package distributed by US EPA and, for those compounds with identified experimental values, compared against measured values. Those data with significant disagreement will be further analysed and will be computed using more rigorous calculations using ab initio and molecular dynamics simulation approaches and thus uncertainty in the data will be minimized. For those compounds with incomplete experimental data sets and for new compounds without experimental data the computational method provides predictive capabilities to fill the gaps in the chemical property database thereby improving and expanding the capability to predict exposure risk to the Warfighter. The resulting chemical property database for the fate, transport, and effects of compounds in complex media will be linked to a database of degradation kinetics for compounds in the natural environment.

3.2.1 Chemical reactivity mapping

There is no product currently available in the field that rapidly predicts exposure risk due to the chemical products of reaction and degradation in the environment. That capability first requires the prediction of viable reaction pathways. A recently developed semi-empirical method computationally generates multistep chemical reaction pathways from the very first step (reagents) to final product including intermediate and speed limited steps. Kinetic parameters are computed from Gibbs free energy changes over a range of temperatures. The speed of reagent decay and product formation can be predicted along with half-lives of key components using the computed kinetic parameters. Reaction kinetics with selected reactive species available in natural surroundings as well as bulk water will also be evaluated for selected compounds.

3.2.2 Phase partitioning

Phase partitioning properties are necessary to assess TIC/M transport in the complex multimedia environment. Of particular concern are mass partitioning from liquid phase release to gas phase and liquid or gas phase release to solid surfaces. In the first case this is because chemicals in the gas phase typically migrate more rapidly from the release point and in the latter case it is because some chemicals may present a long lasting residual exposure hazard in surface soils and the built environment. Electronic structure calculations are planned to compute

several partitioning coefficients such as K_{ow} , $K_{heptane-water}$, K_{oc} , Micelle/membrane interactions using the Gaussian 09, Turbomol, and COSMOmic software packages. Select properties will also be computed using traditional density functional theory and molecular dynamics simulation approaches.

3.2.3 Data analysis/quality assurance

Computational algorithms will be developed to expedite computational data generation using various computational chemistry methods for efficient data analysis and uncertainty reduction among the data already available from the literature. Calculation of correlation coefficients will help to understand the prediction reliability of computational data as well as the quality of the experimental data. Data with greater uncertainty will undergo further analysis and more rigorous calculation to refine the predicted physical and chemical properties. These methods also allow the generation of temperature dependent properties which facilitates high fidelity fate and transport modelling across a wider range of local conditions.

4.0 FATE AND TRANSPORT

4.1 Dynamic Fate and Transport need

Warfighters interacting with water bodies during and after TIC/M release events need actionable information about contaminant exposure risk. Chemicals released to water bodies result in spatially and temporally dynamic concentrations that expand and flow downstream over time. In addition, contaminants are frequently present even when they are not visible and may create a secondary hazard by volatilizing to the air around the stream both of which increase the risk in using in-situ visual inspection as a mechanism to assess exposure potential.

4.2 Fate and transport solution

Georeferenced modelling tools can rapidly identify TIC/M exposure risk in an actionable format. The desired product informs on the extent of chemical spread and the severity of the contamination in terms of hazard risk in a time dynamic presentation. The development of a singular site model for a defined temporal period is not a novel capability but expansion to a non-site specified and dynamic utility that can be applied to multiple sites without knowledge of the chemical compounds a priori requires additional inputs as automated data streams rather than user formatted files (Figure 4).

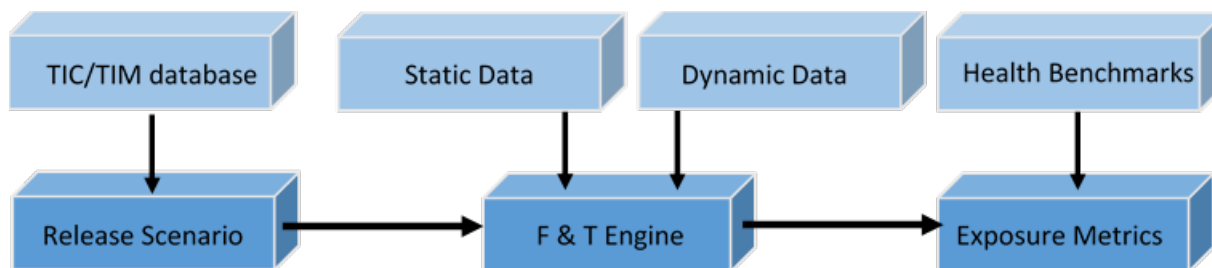


Figure 4, Essential components of the ITCH model system to predict dynamic human exposure

4.4.1 Release scenarios designed for minimal user input

The TICM-INT tools being developed to identify potential sources and quantities of chemicals within a contested AOI are critical for determining potential concentrations in surface water due to chemical releases. Similarly, much of the static description of the AOI can be extracted from georeferenced datasets such as

drainage areas, infrastructure and stream channel locations, and soil types (as informed by the pedoinformatic approach described previously). But, for dynamic modelling, the rate of release is also a critical component. The models for rapid surface water concentration currently available require extensive user input to characterize chemical sources, failure, and release mechanisms because the rate that mass enters the environment to initiate exposure is calculated from detailed physics based scenarios. In the ITCH fate and transport system a guided decision tree approach is being developed that incorporates key information about the range of parameters used for the detailed physics based scenarios. In addition, the system will identify greatest risk scenarios that assume the maximum release rate anticipated for a given type and volume of storage to provide users an upper limit of exposure as well as an expected value or chemical concentration.

4.2.2 Dynamic system of data and models

A second key component of our approach is the inclusion of near real-time and forecasted dynamic data to describe the hydro-meteorological conditions of the AOI. Although average annual properties such as temperature, precipitation, streamflow, wind speed, and wind direction can be used to produce acceptable estimates of the long term average expected behaviour of a system, that is not sufficient to predict the potential exposure for a specific ongoing or near future activity due to the high variability of the hydro-meteorological parameters. Authoritative global meteorological data is linked to ERDCs Streamflow Prediction Tool which performs hydrologic and mass routing. An uncoupled one dimensional advection dispersion model moves the chemical hazard downstream, allowing it to spread over time resulting in concentration time series for each stream reach in the AOI. The advection dispersion model also adjusts the quantity of contaminant in the water column based on solid sorption in the water column and to sediment, partitioning to the gas phase, and degradation kinetics.

4.2.3 Visual Display of Actionable Information

Figure 5 demonstrates the anticipated surface water chemical hazard mapping product. Figure 5(a) shows the concentration time series at a single stream segment location informed by the chemical release scenario, dynamic hydrologic routing, fate determining processes. Comparison between the modelled concentrations and benchmark health effect screening concentrations results in an assignment of risk levels. Figure 5(b) shows the result of multiple stream reach concentration and benchmark comparisons for single time. This type of output could be used to determine gap crossing locations with reduced exposure risk.

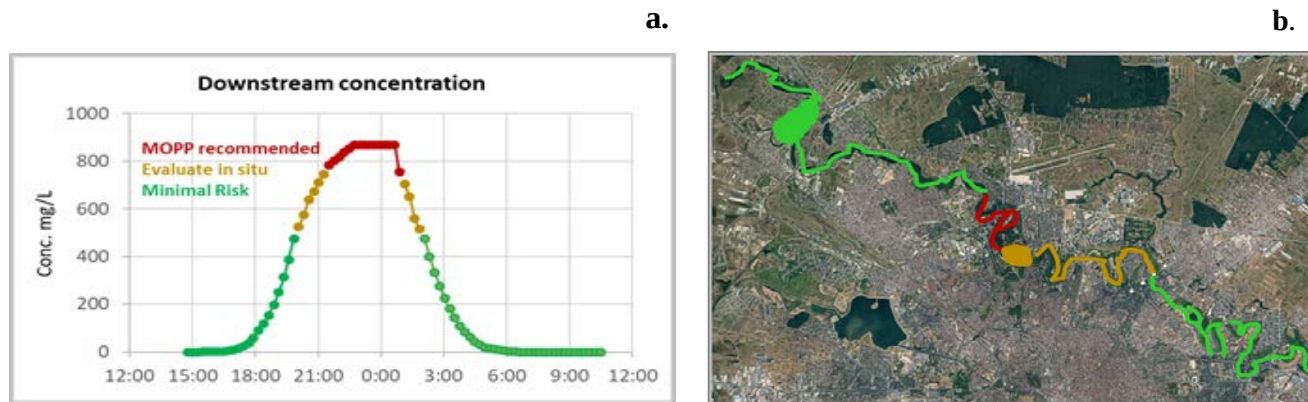


Figure 5, actionable display of chemical hazard in stream

5.0 SOILS

5.1 Soil need

There is a high likeliness that Warfighters will interact with contaminated soils during and after a TIC/M event that is not accounted for in mission planning. Furthermore, exposure via soil contact is not currently modelled as a dynamic source of risk to the Warfighter. But of all the media, soil can be transported with the Warfighter and has the capability to lead to longer exposure durations and therefore higher risk. This can result in significant negative consequences for mission success. The complexity of soils represents a formidable technology barrier in predicting contaminant environmental fate. Complexity arises from the fact that soils are both chemically and physically heterogeneous multiphase materials that respond dynamically to the biological and hydro-meteorological surroundings while reflecting the geologic history of their locale. In addition, human activities can change the chemical and physical behaviour of soils, directly impacting contaminant fate. Urban soils, and those taxonomically identified as anthrosols and/or technosols, are unique and complex materials that can be considered physically and chemically disturbed from their pristine state. The fate and transport of chemical hazards to groundwater, surface water, and the atmosphere in contested urban environments depends on accurate characterization and mapping of urban soils and their expected properties.

5.2 Soil solution

Increased mission readiness and situational awareness can be enabled by understanding TIC/Ms fate and transport in soils, including urban soils. Thus there is a need to identify, classify, and characterize urban soils with similar geomorphological factors globally, and quantify sorption/degradation parameters in these urban soils of selected TIC/Ms.

5.2.1 Development of urban soil analogs

A field collection protocol [2] that is applicable to urban soils will be applied to collect samples at location analogs for AOIs outside the United States. In the urban environment, ongoing soil formation processes combined with the pre-existing pristine soil properties create the unique properties of the anthrosol. Features such as abrupt and clear depositional boundaries, specific and strong chemical features (i.e. stark pH or mineralogy contrast), altered physical features, specific biologic (flora and/or fauna) communities, early stage pedogenesis, or synlithogenesis are specific soil forming factors that can be used to classify an anthrosol. The selection of analog sites is non-trivial requiring the application of a pedoinformatic approach that accounts for factors such as USDA-NRCS and/or WRB classification, parent material, climate, landscape position, and vegetation. Field collections extend to a depth of 24" from the soil surface. A thorough physico-chemical characterization generates base data for a multivariate geo-statistical analysis to determine which of the soil physicochemical factors are tied to chemical fate.

5.2.2 Experimental sorption/degradation of TIC/Ms in urban soils

Multiple processes affect the fate and transport of hazardous chemicals in urban soils including sorption, degradation, and surface complexation. As urban soils are characterized a selection of representative surfaces will be selected for additional studies utilizing microcosm and breakthrough column approaches to evaluate the role of urban soil constituents on chemical retention and the ultimate potential for chemical exposure. Soil constituent factors such as silicates, carbonates, metal oxides, and organic material are likely to be important factors. Soil specific chemical parameters established through batch isotherm and kinetic studies will also serve

as validation experiments for the previously described computational prediction of sorption and reaction parameters.

5.2.3 Digital soil mapping

Chemical and physical soil heterogeneity leads to a heterogeneous fate and transport behaviour in the environment. To utilize the chemical fate parameters determined for urban soils there needs to be a georeferenced capability to identify the soil in the AOI, the heterogeneity of that soil, and the associated physical chemical properties to apply. Digital map layers will enable the linkage between location and appropriate properties which in turn informs which fate determining processes are significant at a given site. This reduces the burden to individually generate fate and transport models for specific locations and increases the fidelity of the model to the range of observed or modelled system properties. The result is an improved prediction of the potential for exposure via soil transference in contested areas.

6.0 PLANNED INTEROPERABILITY WITH OTHER CAPABILITIES

6.1 USACE DRiVE package

Course forecasting, navigation, and routing tools need to account for the fixed physical environment as well as short term changes in conditions. These conditions can include traffic, weather, road hazards, human movement, and other difficult to predict influences on the safety and suitability of a particular course. A real-time analysis of the visual field can provide moment-by-moment information on some of the dynamic conditions, but no tools are currently available that manage exposure risks from the chemical hazards present in contested environments. Given that exposure pathways along soldier routes present a risk for adverse effects that may include physical and/or mental impairment, there is need for a product that can proactively manage exposure risk by assessing the potential for exposure and presenting alternative routing options.

6.2 Drive overview solution

ERDC is developing routing tools that incorporate the products described for the ITCH project above in the DRiVE package. The DRiVE project also incorporates airborne chemical hazards generated from a separate modelling effort but dependent on the same TICM-DB databases and computationally derived chemical properties as the ITCH project. A Toxicological Operational Knowledgebase System (TOKS) is planned to expand on the TICM-DB database with biological effects of TIC/Ms and conventional chemical, biological, radiological and nuclear threats. Multiple acute inhalation toxicity reference values will be leveraged to develop probabilistic assessments of risk. Routing decisions in DRiVE utilize probabilistic risk and cost function game theory rather than shortest travel distance or travel duration to choose acceptable routes. Thus, risk due to multiple sources can be accommodated in route selection.

7.0 CONCLUSIONS

7.1 Implications of this work

Future mission planners will have increased capability through the ITCH tools to assess potential lethal environments that may be encountered during active engagement. Sparse ground level data on the location and quantity of TIC/Ms in the urban environment will no longer limit the ability accurately assess chemical hazard exposure risks. Utilizing advanced computational methods to determine the properties that govern the fate of

chemicals in the environment, higher fidelity modelling will be available for a comprehensive list of chemicals and chemical breakdown products. With near real-time capability to ingest and process hydro-meteorological conditions and the ability to predict soil properties in urban environments the dynamic fate and transport of TIC/MS in surface water and soils will also be predictable. This will reduce the risk of impaired soldier functions or mortality due to unplanned exposures and increase tactical advantages during operation and sustainment in contested urban environments.

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Modelling & Simulation for Underground Operations

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INTRODUCTION

Due to the increasing volume of traffic and the resulting efforts of the society to reduce traffic in urban areas and settlements, to build bypasses or due to the topography to move this partially underground. Resulting in an increasing number of complex traffic and safety concepts, which include underground infrastructure. From a fire safety perspective, hazards are manageable and risks are largely calculable. The scenario of a dangerous goods accident in a road tunnels or the release of chemical agents into underground facilities is treated very sparingly (if at all), neither are military concepts for underground operation. However, the attack with Sarin on Tokyo's subway in 1995 shows that underground facilities in particular have a particular vulnerability here.



Figure 1: complex emergency Tokyo 1995

When assessing tunnels, quantitative risk analyzes are carried out by default, but these primarily relate to the effects on personal safety in the tunnel and also on the tunnel itself. Concrete considerations regarding the safety of response units are not carried out. Tunneling projects of the trans-European road network have a special significance throughout Europe and are subject to specific directives of the European Union. First and foremost, this is Directive EU No. 2004/54 / EC (2004). The Road Tunnel Safety Act transposed Directive EU No. 2004/54 / EC (2004) into the Austrian legal system. The road tunnel safety law for federal highways is enforced in accordance with federal highway law and a tunnel length of more than 500 m. For tunnels outside this scheme (tunnels on provincial, district and municipal roads or tunnels less than 500 m in length), the Road Tunnel Safety Act will apply *mutatis mutandis*.

For the transport of dangerous goods by road (according to ADR or dangerous goods transport law) restrictions apply to the passage through road tunnels. National restrictions are also found in BGBl. II No. 395/2001 (2001). Further traffic prohibition regulations are carried out on the basis of the road traffic regulations. In addition, there are nationally the holiday travel ordinance, which regulates driving bans on

weekends in summer, as well as the "regulation on the restrictions for transport units with dangerous goods when driving on motorway tunnel", which regulates and restricts the passage through single-tube road tunnels for dangerous goods transport. The topic of the transport of hazardous substances in tunnels can be found in numerous legal documents and guidelines. For the planning, dimensioning, commissioning and accident management, the Austrian Road-Rail-Traffic Association provides the Road Regulations, which are supported by the Federal Ministry of Transport, Innovation and Technology of the motorways and freeways financing corporation (ASFINAG) and the federal states and were declared binding in the area of federal highways.

For tunnels, a quantitative risk assessment of hazardous substance transports with a risk-oriented assessment approach is currently under consideration of alternative routes. Essentially, this only derives from an allocation with regard to any traffic restrictions for the transport of dangerous goods and the restriction category. Furthermore, a quantitative tunnel risk analysis is carried out to determine the overall risk. In addition to dangerous goods accidents, the risk of tunnel fires and mechanical accidents is also considered. On the one hand, this results in the assignment to a hazard class and, on the other hand, a requirement for additional risk-reducing measures. These consist e.g. from structural measures in the area of drainage and aim to quickly collect liquid pollutants and divert into water protection systems. Furthermore, structural measures are taken to prevent the spread of fire through the drainage system. Structural measures for the reduction, e.g. of explosive effects are not yet sufficiently investigated or not available. On the other hand, there is a limited detection by the installation of ventilation systems, as well as permanent metrological monitoring of carbon monoxide.

STATE OF THE ART

The general level of knowledge regarding the propagation and effect of hazardous substances in underground traffic void structures is rather low. Pollutant dispersion calculations are practically only for smoke and traffic emissions. Experience in the field of release of chemical agents (toxic industrial materials and chemical warfare agents) is very limited. The current knowledge is based mainly on theoretical considerations without real scientific proof. Dangerous goods accidents in tunnels, as well as the release of chemical agents in underground facilities in general is a particular challenge for emergency services. Long approaches, a large number of potentially vulnerable people, complex building services and restrictions in the field of personal protective equipment of the emergency services, limit the options for action.

Current scientific studies on accidents in tunnels mainly relate to the fire scenario. Although in alarm and operational plans, hazardous goods events are generally dealt with, for lack of in-depth knowledge on this topic, as well as mostly missing operational concepts, only very basic specifications are made here. Here are detailed calculations, ventilation concepts and application concepts, which allow to dominate tunnel fires largely. Already the decision on meaningful fan control at dangerous goods release leads regularly to discussions. This shows the relative uncertainty as a result of insufficient knowledge and lack of experience. Different ventilation concepts for flammable gases, toxic heavy or neutral gases depending on the tunnel infrastructure are not available. In most tunnels ventilation systems are taken out of service in the event of an incident, the advance of forces is thus not actively supported. In railway tunnels are largely no ventilation aides available. It is also not known how events (such as explosions) and ventilation will affect outside the tunnel. In subway systems in particular, many exhaust vents are located directly in urbanized areas and represent a potential source of danger in the specific case. Corresponding impact analysis away from traffic-related pollutant emissions is missing here (toxic heavy gases, warfare agents, combustible gases, etc.).

The field of tunnel fire has been intensively treated by the emergency services for many years. The deployment concepts are based on many experiments, exercises, but also on operational experience of recent years. Due to the developments in the automotive industry, the energy supply (natural gas, hydrogen, etc.) and the change in the security police situation, focal areas have shifted and expanded. The area of dangerous

goods as well as chemical agents in the broader sense are currently only present in the risk analyzes which are generally used for the assessment of tunnel safety. There is a need for research throughout the event-handling system of chemical agent events in underground facilities.

Recent advancements in augmented and mixed reality applications now enable the use of the technology in corporate settings. In industry, virtual and mixed reality is used to train work processes. Corporations, authorities and military organizations worldwide are using mixed reality glasses or are conducting research to integrate them into their existing infrastructure. Real time 3D reconstruction and combination of 3D data, as well as supplementing it with external information, is an innovation that can be used for simultaneous localization and mapping (SLAM) algorithms that are used in a variety of domains such as robotics and autonomous driving. Automated detection and classification extend the state of the art concerning robust algorithms that are resistant to data inconsistencies (motion blur, distortions, smoke...) and can work with a small amount of data. The standardized interfaces innovate the adaptability towards highly dynamic processes, which are prevalent in emergency operations underground.

EVENT DETECTION AND VERIFICATION

In the field of sensors, there are currently systems for early fire detection, for dangerous goods accidents or the release of chemical agents such systems are usually not available. Currently mainly the permanent metrological monitoring of carbon monoxide and visibility clouding is considered. It is currently not known whether due to the propagation behavior of different substances early detection with sensors is even possible or where the use of sensor systems is targeted.

WARNING AND ALARMING

Although, in operational plans, hazardous goods events are generally dealt with, for lack of in-depth knowledge on this topic, as well as mostly missing operational concepts, only very basic specifications are made here. Already the decision on meaningful fan control at dangerous goods release leads regularly to discussions. This shows the relative uncertainty as a result of insufficient knowledge and lack of experience. Safety and shut-off areas can only be determined on the basis of assumed effects, and there are no definite studies on the endangerment of emergency personnel depending on the specified operational areas.

SAFETY AND SECURITY

On-site security requires a thorough understanding of the implications of different scenarios, especially when comes to military intervention. Currently largely unappreciated is the impact on operational personnel deployed in such events. In the area of tunnel firing, the targeted design of safety equipment has ensured that, on the one hand, escape and, on the other hand, intervention by emergency personnel is possible. At present it is still unclear how an intervention in tunnels can be designed in case of increased danger of explosion or after the release of toxic substances or what risk exists for response services. It lacks an evaluation basis for the decision where and under what conditions can be intervened and what technical and tactical possibilities are there to allow intervention.

Currently used types of protective clothing and respiratory protection systems allow only very short operation times, which cannot be used in underground facilities due to the long transportation and deployment times (even at short cross-pass distances). Also unclear is the subject in case of incidents within response units or respiratory emergency. Rescuing intervention personnel with chemical protective suits is an additional challenge compared to standard emergency response. Again, the above parameters of long distances and physical burden, further has main impact on air supply and mission time. Basis for a rescue

and intervention concept could be on the one hand ventilation measures, but possibly also the use of new technologies.

Due to the existing research-related deficits, further developments in connection with the challenges above are hindered and innovations slowed down. The complexity of the topic makes a cooperative research approach necessary to develop the scientific basis for interventions in the presence of chemical agents in underground facilities. Especially with regard to the technical equipment of tunnels and with regard to new ventilation concepts in conjunction with the measures of the emergency services. In addition, results provide starting points for further research in the field of respiratory protection or the personal protective equipment.

OUTLOOK

With the results it should be possible to create an evaluation basis for the intervention in underground facilities. It is to be clarified under which conditions interventions are possible. For this purpose, the focus will be on the spread of CBRN agents and the effects of explosives. Further aims are to identify gaps in risk analysis of tunnels and to identify starting points for innovations in enhanced equipment. By modelling and simulation activities for underground operations the following results are expected:

- Analysis and documentation of organizational aspects of operational concepts
- Analysis of TTPs and development of CONOPS
- Behaviour of neutral, light and heavy gases or vapors
- Investigation of fire and explosion impact
- Evaluation of results in terms of risk areas for civilians and operational personnel
- Determination of effects of different analyzed scenarios on the infrastructure (explosion pressures, corrosion effects, temperature profiles, etc.)
- Analysis of the effects of pollutant releases in the environment of above-ground facilities
- Preparation of hazard and risk information as a basis for the development of a rating system

Representation of Dynamic Synthetic Environments in Distributed Simulation

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ABSTRACT

Current practices, standards and technologies are aimed at achieving correlated static synthetic representations of Defence operational environments across distributed simulation systems. However, real world operational environments are dynamic in nature. Weather varies with time and place, and the terrain is affected by both natural effects (e.g. heavy rainfall, snow, flooding) as well as the effects of force behavior, such as munitions damage to buildings and infrastructure. Where multiple simulation systems are federated, both the static and dynamic representation of the operational environment needs to be consistent.

This paper describes work being carried out by the MSG-156 Task Group (TG) to investigate simulation architectures, processes and standards aimed at achieving improved and consistent representations of dynamic environments across simulation systems. This includes the representation of weather data in simulation, processes to dynamically modify the terrain and protocols for simulation systems to retrieve the current state of the simulated operational environment. Modelling and Simulation as a Service (MSaaS) is assessed as being a key enabler required to achieve this.

This paper describes a set of Use Cases and the Conceptual Models that has been derived from these Use Cases. A proposed architecture for achieving a consistent dynamic synthetic environment is also included, together with a description of planned experiments to evaluate the proposed solution.

INTRODUCTION

Motivation

Defence operations are performed in a world where the environment is dynamic and where weather and warfare effects have an impact on operational capability, including platform and systems behaviour. Throughout history weather has been a fundamental element to the decisions made on the battlefield at the tactical through to strategic levels. The MSG-156 Task Group (TG) recognised a capability gap in current defence Simulation and Synthetic Environments (SEs). This has been identified as a lack of consistent representation of dynamic environments across simulation systems, specifically the representation of meteorological data and physical warfare effects and associated 2nd and 3rd order effects on the operational environment. Examples include the effects of rain on the terrain surface which can affect ground vehicle mobility, the effects of cloud formations and rain on airborne sensors, the effects of wind on air platforms, e.g. Unmanned Air Vehicles (UAVs), and the effects of munitions damage to the terrain surface (e.g. craters) and road infrastructures which impact route planning. Representation and effects of weather conditions (e.g. rainfall, wind, temperature), and climatic conditions (e.g. desert, arctic, etc.), within simulation systems has

traditionally been poor, mainly due to lack of requirements and limitations in technology. This has resulted in disjointed approaches which have typically resulted in,

- two dimensional representations of clouds for ground training systems which cannot be re-used for airborne training systems;
- atmospheric modelling which does not match reality; for example cloud systems do not accurately affect the aerodynamic behaviour of air vehicles;
- no link between representation of weather visually (e.g. rain and fog), and its effect on the environment (e.g. 2nd order changes to the state of the ground), systems, equipment and human behaviour;
- disparities in weather representation within heterogeneous distributed simulation systems where some systems represent weather, some do not, and some simulate contradicting weather.

Current simulation standards based technologies and practices are aimed at achieving correlated static representations of the outside world environment based on sharing common environmental datasets and re-using environmental databases. While some simulation systems do support dynamic effects that reflect weather conditions and physical warfare damage, these are often pre-scripted and are not correlated across federated simulations. Subsequently, the extent to which dynamic aspects of operational environments are represented in current simulation systems is limited and often bespoke to a given simulation, resulting in different effects being represented across simulation systems. This limits the level of simulation interoperability that can be achieved when there is a need to configure a larger scale simulation based on networking a number of distributed simulation systems in order to meet a given requirement.

Where simulation is used for joint collective training, experimentation, support to defence equipment acquisition, mission planning or evaluation and test, these dynamic aspects need to be supported in a common and consistent way across dissimilar simulation systems. Current best practices, standards and technologies struggle to achieve correlated representations of the simulated operating environment. The inclusion of dynamic aspects of the environment will make this struggle even more challenging, thereby underlining the need for more extensive methodologies and technologies to achieve correlated environments in distributed simulation systems, including Computer Generated Forces (CGFs), Human-in-the-Loop (HITL) platform and sensor simulations. To ensure that simulations can be setup and used more effectively in the future by NATO and NATO Partner Nations it is important that correlation of dynamic operational environments in simulation can be achieved in a more responsive manner both in terms of cost and time.

Related work

Fully dynamic Synthetic Environments (SEs) have been on the 'wishlist' of the Modelling and Simulation (M&S) community for some time and work on this topic has already been performed in the 1990's [e.g. Moshell1994]. However, to date we are still not much closer to a commonly agreed approach to achieving dynamic SEs that provide correlated effects across distributed heterogeneous federate simulations. Initiatives in the past have aimed to extend the existing Distributed Interactive Simulation (DIS) and High Level Architecture (HLA) simulation interoperability standards with messages to support changes in the state of the SE, but their acceptance and implementation in simulation systems has not been widespread.

On the level of a single simulation system (or a federation of systems developed by the same supplier), there are many interesting examples of dynamic changes to the SE. For instance, a Forward Air Controller simulation might feature destructible targets such as buildings and bridges, and a combat engineering simulator might contain a comprehensive and realistic model of soil and its deformation behaviour for e.g. digging trenches. However, each of these simulations implement only part of the wide range of possible dynamic SE interactions and in their own proprietary way, with no concern for communicating these changes in a standardized manner.

Another factor that might have hindered investments in dynamic SE capabilities in the past is the complexity and computational expense of simulating dynamic effects in a realistic way. A physics-based simulation of munitions damage to a building was simply not feasible in real-time. Therefore, methods employed included having a small set of pre-modelled damage states, which often did not match the actual point of impact and munition type employed, lessening the value of such dynamic interactions.

The increase in CPU/GPU computing power over recent years has now allowed for complex, physics-based deformation and destruction algorithms to run in real-time. In the entertainment gaming industry, this has led to numerous convincing examples of real-time destruction and deformation (for instance, physics-based building destruction in the Frostbite engine [EADICE], powering the Battlefield series of games, or the complex terrain deformation and trafficability model of SpinTires [Oovee2014]). Furthermore, in the research fields of computer graphics and simulation there has been substantial progress on real-time, physics-based techniques for a large number of relevant dynamic effects. A full discussion of the current state of the art is out of scope for this paper, but can be found in a recent survey article on this topic [Smelik2019].

The M&S community is currently investigating new approaches to delivering simulation for defence, transitioning from complete simulation systems hosted on dedicated hardware to access to more modular simulation components and services which are either readily deployable or remotely accessible on cloud-based servers [MSG-136]. This transition not only promises to reduce deployment and configuration costs and increase flexibility, but even more important in the context of synthetic environments it offers a more manageable way to enable correlation across federate simulations compared to current practices, and scalability in terms of data distribution and computation power by leveraging the cloud-based resources.

Taking into account the increase in processing power and network bandwidth, and the move from standalone, large simulation systems to modular cloud-based (micro-)services, there are now opportunities to work towards fully correlated dynamic synthetic environments.

MSG-156 Research Question

Given the importance of a realistic dynamic environment within simulation systems and given the challenges that are still faced to achieve this in a Mission Training through Distributed Simulation (MTDS) environment, in 2016 a NATO MSG Exploratory Team ET-045 was setup to investigate this topic. Based on the recommendations of ET-045 [ET-045] in 2017 a new NATO MSG task group, MSG-156, was setup with the objectives to:

- Define best practices, required methodologies, technologies and inform requirements for standards needed to achieve a correlated dynamic SE in future distributed simulation exercises.
- Evaluate methodologies and technologies through concept experimentation where needed.

MSG-156 is focused on the following aspects of a dynamic SE:

- Achieve a **dynamic terrain** that is shared between the participants of the distributed simulation, taking into account the natural, human geophysical and force engagement effects that influence the terrain. Methods and technologies are needed to deform the SE in a common and consistent manner.
- Achieve **variable weather** that is shared between the participants of the distributed simulation. Which aspects of the weather do need to be represented and which data sources are available to introduce the weather in the simulation? Which methodologies and technologies are needed to integrate the weather consistently in the simulation and to ensure that the weather affects the participants in a common and consistent way?

Representatives from France, Germany, Netherlands (chair), Norway, Slovenia, Turkey and the United Kingdom have joined MSG-156 and are working on these research questions.

Paper outline

This paper provides an overview of the MSG-156 TG progress to date, its plans for practical experimentation and future work.

Section 2 of this paper discusses the proposed approach to addressing the TG objectives. The section is divided in a number of subsections, describing example Use Cases of dynamic synthetic environments that were used as basis for group discussions, the development of conceptual models to understand how elements of a dynamics SE and simulation entities interact, and a technical architecture based on the MSaaS paradigm. Section 3 provides an overview of planned experiments which will be used to test and de-risk the concepts and the architecture. Finally, Section 4 provides a short summary of the paper, and discusses the expected results and future work beyond the scope of MSG-156.

APPROACH

Use Cases

The technical approach employed by MSG-156 is based around four Use Cases which will be used as a basis for experimentation on approaches and prototype methods relevant to the deployment, integration and execution of simulation scenarios which include the correlated representation and disturbances of weather (i.e. weather effects) on force behaviour.

- Close Air Support (CAS);
- Air engagement in realistic weather;
- Trafficability influenced by weather;
- Terrain modifications.

Use Case #1 “Close Air Support (CAS)”: During a CAS mission the Forward Air Controller (FAC) on the ground and the Air Crew in the air need to visually identify the same target that should be attacked. This is done by describing the object using a standard report and by voice communications. Using the sensors of the aircraft, including a targeting pod, the air crew will aim to identify the correct object. Once the object has been identified the air crew will start the weapon delivery and afterwards the weapon damage will be assessed by both the FAC and the air crew to decide if the target has been destroyed or not. The trainees in the different simulation systems need to be able operate and communicate in such a way that they can identify the same target.



Figure 1: Close Air Support team (source Defensie.nl)

Use Case #2 “Air engagement in realistic weather”: An Unmanned Air System (UAS) is deployed to conduct Intelligence, Surveillance and Reconnaissance (ISR) activities and identify a ground target. The UAS is configured with weapons, on-board radar and an Electro-Optic (EO) sensor. As the UAS carries out its reconnaissance of the operational area a weather front passes through bringing increasing cloud cover and some precipitation. An enemy manned aircraft is tasked with destroying the UAS. During the air-to-air engagement sensors on the airborne platforms are tracking each other. The clouds sometimes block the visual line of sight between the two airborne platforms and precipitation in the atmosphere introduces disturbances and degradation on the sensors. An air-to-air missile is subsequently fired at the UAS. The seeker of this missile will track the UAS and guide the missile to the target.

Use Case #3 “Trafficability influenced by weather”: A convoy of armoured vehicles and supply trucks is traversing a difficult mountainous and densely vegetated terrain on a multi-day trip to resupply an isolated Forward Operating Base. Not all local roads are paved and in good condition, and heavy rainfall causes some of the dirt roads to become slippery, forcing the convoy to advance at reduced speed. The rain changes to snow, and with the decreased visibility and the trucks getting stuck in the high snow volumes, the convoy commander no longer considers it safe to continue and decides to take a long detour using only paved well-maintained roads.



Figure 2: Example of vehicle trafficability influenced by weather (source Defensie.nl)

Use Case #4 “Terrain modifications”: A combat engineering unit prepares a defensive position for infantry in open terrain by digging a network of trenches. Later on, opposing forces applies a barrage of artillery fire on the reinforced positions, resulting in numerous large craters in the terrain and damage to the trenches. Opposing infantry units and vehicles now use these craters to advance on the defensive position under cover.



Figure 3: Example of craters in a terrain (source Defensie.nl)

Conceptual Models

To get a better understanding of the various concepts that are involved in a dynamic SE and to understand how these concepts are related to and influence each other, the MSG_156 TG created conceptual modelling diagrams for each of the four Use Cases described above. These four diagrams focus on the following aspects of a dynamic SE, i.e.

- The influence of terrain and weather on the trafficability of vehicles.
- Terrain and object deformation due to weapon effects.
- Flight dynamics of aerial vehicles influenced by weather.
- Sensor performance affected by weather.

Figure 4 shows the resulting diagram for the influence of terrain and weather on the trafficability of vehicles. The diagram shows that the trafficability node at the center is influenced by the characteristics of the vehicle (e.g. weight, tracked or wheeled), the surface conditions and the surface characteristics (e.g. slope) of the terrain. The surface conditions on the other hand are affected by the terrain characteristics and by precipitation, e.g. an unpaved road can get muddy when it rains, while a paved road mainly gets wets with some puddles. In the end it is all about the driving behaviour of the driver of the vehicle who determines the speed and thereby the movement of the vehicle, and this driving behaviour is influenced by the surface conditions and by the visibility (e.g. how well the driver can see the environment).

The other three conceptual modelling diagrams show the same kind of information for the topics that they address.

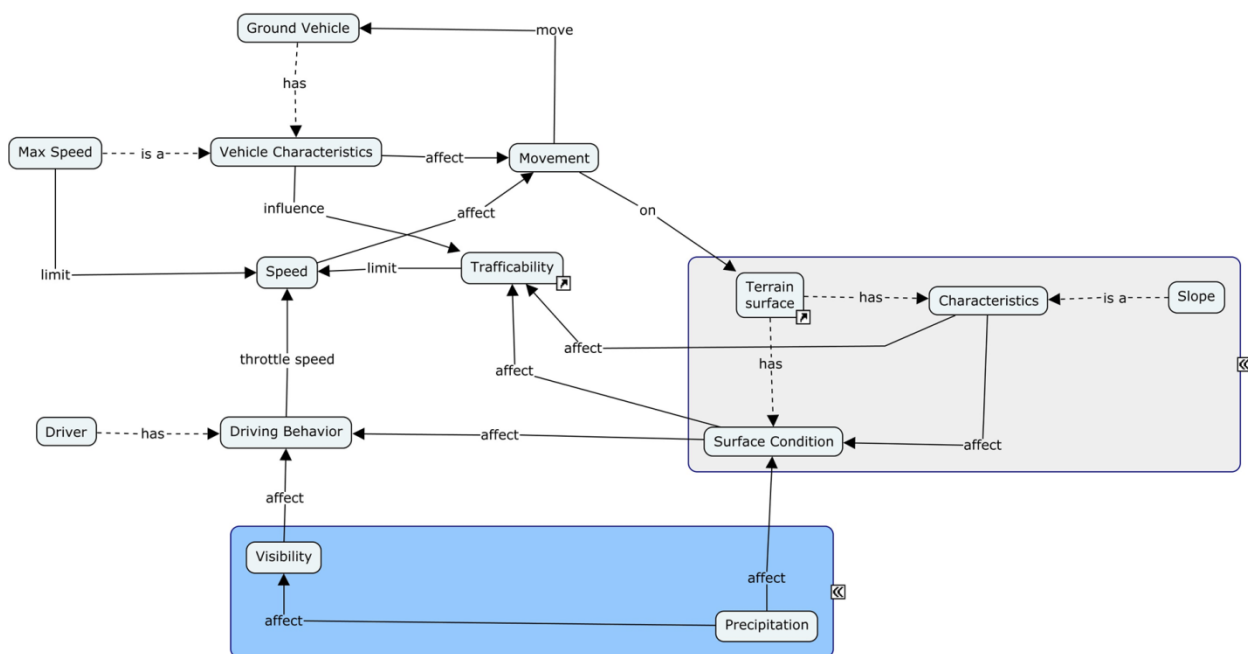


Figure 4: Conceptual modelling diagram for the influence of terrain and weather on the trafficability of vehicles

In the conceptual modelling diagram above the various concepts that play a role in trafficability are listed and it is also shown how they are related to each other. These concepts need to be implemented in the simulation environment to be able to simulate a dynamic SE in a realistic way. Therefore the information from these diagrams helped the TG in defining the proposed solution architecture that is discussed in the next section. The various aspects that have been identified in the conceptual modelling diagrams have to become

the responsibility of a specific model or component within the simulation environment, e.g. a terrain weather interaction service might get the responsibility to calculate the influence of the weather on the terrain surface. By checking which concepts are related it also becomes possible to identify the interfaces that are needed to communicate the required inputs or outputs between the various simulation components, e.g. the model that calculates the trafficability needs to receive information about the terrain surface condition from the SE and the output of the trafficability limits the speed of the vehicle so that needs to be communicated to the ground vehicle dynamics model.

The conceptual modelling diagrams are therefore a tool that helps to define the responsibilities of the various simulation models in a logical way, since the diagrams help to understand the real world interactions that are being represented. Once these model responsibilities have been identified, the interfaces needed to exchange information can also be defined in a logical way.

Proposed Initial Architecture

A recent development within the NATO MSG community is to propose MSaaS as the forward-looking approach for distributed military simulation. A M&S service is a specific M&S-related capability delivered by a provider to one or more consumers according to well-defined contracts, including service level agreements (SLA) and interfaces. A distributed simulation is composed of either existing, reusable or newly implemented dedicated services.

Some of the advantages of the MSaaS approach have been covered in the Related Work section. The TG initially also considered following a more traditional approach, based on using existing infrastructure and protocols (i.e. DIS and HLA), to implement a correlated dynamic SE. However, there are a number of limitations when using more traditional approaches, notably the difficulty of maintaining a correlated SE across all federates while dynamic changes are being made when not working with a centralized SE model, but instead having each federate maintaining its own SE instance. This would require, among other things, standardized deformation algorithms to be employed and expected outcome of dynamic effects (e.g. munition detonation on soft soil). Experiments have been performed in the past based on sending complete delta's of SE data layers after dynamic interactions have occurred, packaged as DIS Protocol Data Units (PDU's) or HLA messages. However these approaches did not get much traction. Furthermore, DIS/HLA are not really designed for the distribution of large dynamic data layers to federate simulations, and it is typically more efficient to have federates only pull the data layers relevant to their simulation and area of interest.

Considering the above, and in order to come up with future proof concepts, and to maintain links with other ongoing MSG activities including MSG-131/MSG-136 ("Modelling and Simulation as a Service (MSaaS) – Rapid deployment of interoperable and credible simulation environments"), and MSG-164 ("Modelling And Simulation Aas a Service - Phase 2"), the group decided to follow the MSaaS approach. Ideally new service components, reusable for other experimentation will arise from this TG's work.

High Level Service architecture

Static terrain and weather

The high level service architecture looks simple, as long as the aspects of dynamic terrain and weather are not regarded. In the context of work being carried out by this TG terrain and weather data is transferred into a data repository which provides quality proofed and optimized data to the Terrain Service and the Weather Service. Both services deliver the data to the connected federates using service interfaces. Figure 5 shows this architecture.

Dynamic terrain and weather

For handling dynamic terrain the architecture has to be expanded. The static part remains and delivers the initial supply of the data. The aspect of dynamic terrain means that the terrain data may change either due to the effects of weather or federate simulations (e.g. air to surface missile). Examples include heavy rain, causing impassable ways, or weapon impacts generating craters or destroying buildings.

In order to support dynamic terrain effects Terrain Interaction and Modification Services (TIMS) are introduced. Such a service's task is to receive events, calculate the impact on the terrain and finally update the terrain using the terrain service. To fulfil the task the TIMS pulls the terrain data of the area of interest, processes the modification and delivers the modified data back to the terrain service. The terrain service requires additional capabilities, which includes being able to receive modified content and update the data repository in order to provide the modified terrain data. Furthermore the Terrain Service has to push change notifications to inform the other federates. Figure 6 shows the resulting architecture.

For reasons of clarification there are two classes of TIMS. The Federate-Terrain Interaction and Modification Service responsible for modifications induced by federates and the Weather-Terrain Interaction and Modification Service responsible for processing weather related impacts. Technically they should use the same interfaces.

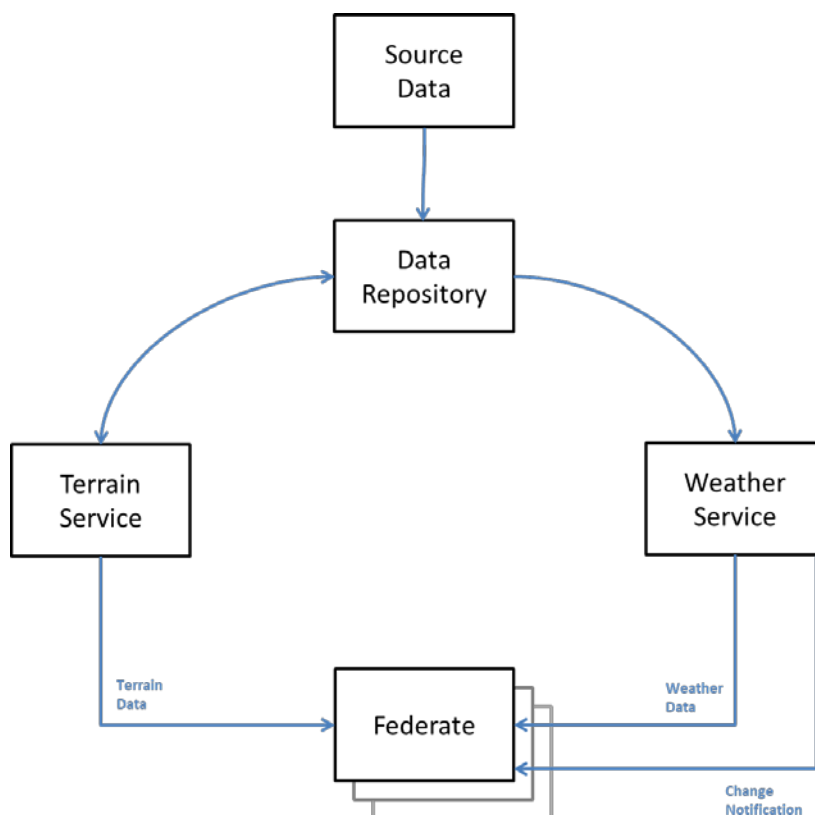


Figure 5: Solution architecture for static SE

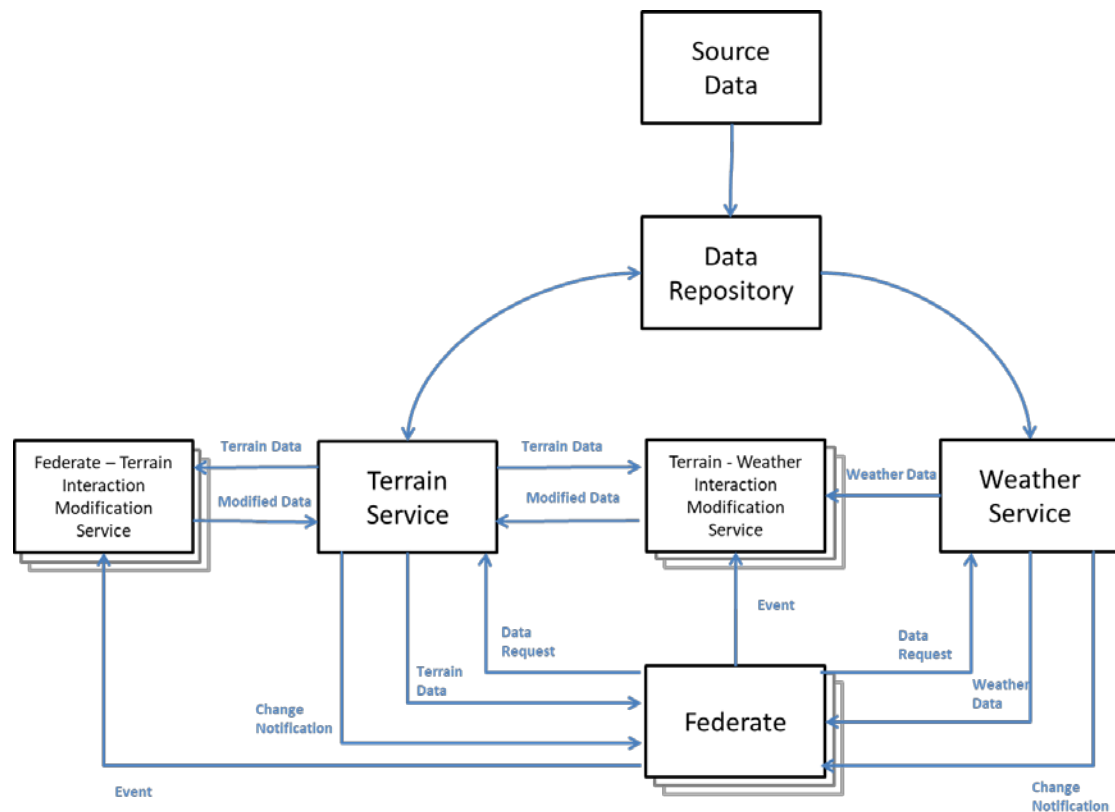


Figure 6: Solution architecture for dynamic SE updates

Examples

For comprehending the diagram above the two following examples may be helpful:

Impact of an explosive device:

- A federate launches an explosive device and sends that event qualified with necessary parameters to a Weapon Effect Service (WES), which is an implementation of a Federate-TIMS.
- The WES receives the event, pulls the affected terrain data, calculates the impact, regarding the weapon parameters and the terrain and transfers the update to the Terrain Service.
- The Terrain Service updates the data repository and sends a Change Notification.
- All federates, which require the changes 'subscribe' to the modified terrain.

Change of weather conditions:

- The weather service sends a Change Notification relaying that heavy rain has started in an area.
- The Weather-TIMS fetches the terrain and weather data of that area and recalculates the soil moisture layer for example, and pushes the update to the terrain service.
- The Terrain Service updates the data repository and sends a Change Notification.
- All federates, which require the changes pull the modified terrain.

Interfaces

The dynamic changes either can be calculated equally in every similar system or the dynamic changes can be shared using proprietary data flows. In the context of MSaaS a simulation environment is likely to consist of several heterogeneous systems. Thus an agreement for the interfaces has to be found. The MSaaS approach requires for services to exchange data, and because no simulation specific standard for these services exists new and well proven service standards have to be introduced. These services are the main interface for the access of the environment and the weather data. Remote information interchange is a great advantage of that approach. Any system on any platform running on any operation system can retrieve data without integrating any special programming library or any other proprietary software which may require a different runtime environment. For further consideration two general data types have to be looked into, i.e. Raster data and Vector data.

Raster data

The type of service to be used depends on the data types the federation has agreed on. In the context of MSG-156 raster data is predominantly used. This applies to elevation data, aerial photographs and weather data in general. Raster data usually is transported as image data, which can be delivered by two Open Geospatial Consortium (OGC) Services:

- The Web Map Service (WMS) delivers georeferenced imagery; this can be aerial imagery itself, which is part of the environmental dataset or cartographic information, which can be derived from the vector data contained in a SE service.
- A Web Coverage Service (WCS) provides coverage data like elevation, air pressure etc. as input for calculations, rather than displaying the raw data itself. The WCS provides the original data and has the capabilities to provide the description of the semantics as well. An important point for dealing with dynamic terrain is the WCS-T Extension. This extension (T standing for transactional) delivers the definition of mechanisms for uploading coverages to a server or modify existing coverages on it.

Raster/image data is very common and easy to handle, which makes it a good choice to be used in heterogeneous infrastructures. However, the raster structure itself can include coarse resolutions which do not deliver a precise representation of the situation; linear structures are especially problematic. To achieve a more precise spatial representation (e.g. of building footprints or roads), the resolution has to be increased which results in the amount of data to be transferred potentially being very large.

Vector data

To avoid storing and exchanging huge data amounts vector data is used. Vector data is not made up of a grid of pixels. Instead, vector graphics are comprised of vertices and paths, which define points, curves and polygons. This allows the exact representation of (geo-) data with very small datasets.

The OGC also provides a service for this kind of data, i.e. the Web Feature Service (WFS), which can have a transactional behaviour as well. But there is the issue that the vector data format has to be defined and agreed on. The starting point for that is XML/GML which the WFS concept requires and which can be enhanced to support specific semantics. This concept is very suitable for handling vector data like road networks or other positions of infrastructure in the training environment.

Although this way of interchanging data has a lot of advantages, it is very difficult to implement even in experimental environments. The reason is that it is often not possible for legacy systems to adapt any other data source, so there are ongoing discussions how to deal with that type of data.

Weather FOM

The requirements for a weather data FOM are being reviewed and assessed by the TG to identify which information should be included in such a FOM and which elements of weather are most suitable for use in simulation systems. This activity is based on an existing draft METOC data FOM (ref: MSG-163) and inputs from other related FOM activities being carried out by suppliers. The aim is to have an agreed draft FOM module for weather.

Links with other task groups

MSG-156 is cooperating with other MSG task groups while carry out this work. Most notably this is with the following groups:

- MSG-163 ("Evolution Of Nato Standards For Federated Simulation"), which is working on expanding the NETN FOM with additional modules; one such module is a weather or METOC FOM.
- MSG-164 ("MSaaS Part 2"), which is working on MSaaS technologies; since the solution architecture of MSG-156 is MSaaS based, the outputs and key findings of MSG-164 (and MSG-136) will be taken into account. The specific services MSG-156 is experimenting with are examples of implementations of the MSaaS concepts that MSG-164 is working on.

Experimentation

As part of the work of MSG-156 an experiment is planned to partially implement and evaluate the service-based architecture for dynamic SEs. It will also serve as a demonstration to highlight the potential of correlated dynamic synthetic environments realized using a service-based architecture. The experiment infrastructure and setup is planned to be implemented over 3 iterations and be finished in May 2020, after which the experiment and demonstrations are scheduled to run.

Taking the requirements and four Use Cases described above, as input, a military simulation scenario has been developed to drive the experiment. It aims to cover a variety of types of federates involved (CGF, human-in-the-loop, ground and air platforms) and to support a range of dynamic effects and events within a small scenario scope (scenario duration and geographic area). The focus is on the role of dynamic weather in simulation scenarios and how it affects the terrain state, trafficability, visibility and sensor performance, as correlated dynamic weather effects offer huge potential benefits for distributed military simulations, e.g. increased realism, higher training value, more interesting scenarios.

Below follows a brief description of the scenario script:

A convoy consisting of armoured vehicles and supply trucks leaves early in the morning on a long trip to resupply an isolated Forward Operating Base. A large part of the trip involves traversing a difficult mountainous and densely vegetated terrain, as this is the most direct route to the FOB and avoids the main roads in the valley, which the convoy commander considers to be unsafe due to recent IED incidents and other insurgent activities.

During the morning the fair weather quickly deteriorates into heavy rain showers. Since most of the mountain roads are unpaved and not well maintained, these dirt roads become slippery, forcing the convoy to advance at reduced speed. The rain then changes into snow and with the decreased visibility, tricky roads and the trucks getting stuck in snow, the convoy commander has no choice than to leave the mountains and take a long detour through the valley, where the paved and well-maintained roads are less affected by the weather.

A manned aircraft is now launched from the main base to provide air support and route clearance for the convoy. Due to the weather and thick cloud coverage, visibility is low and sensor performance is degraded. Therefore, it is unable to detect an ambush by local insurgents in time.

An IED is triggered remotely in front of the lead vehicle. The armoured vehicle and its crew are unharmed, however one of the supply truck suffers mechanical damage, halting the convoy. Immediately after this, the convoy receives incoming mortar fire from a compound situated on hills nearby. The convoy commander requests assistance and a Quick Reaction Force (QRF) is tasked to link up with the convoy and provide force protection for the duration of the trip.

Meanwhile, the manned aircraft uses its IR sensors to quickly determine the origin of the fire and engages the opposing forces, thereby damaging the compound. The convoy is mostly undamaged, but large craters have been struck in the road surface and terrain, forcing the convoy to back up, and reroute off-road, again delaying the convoy's progress. The QRF is able to link up with the delayed convoy and no further incidents occur during its course through the valley.

Late in the day, the convoy starts crossing a bridge over a wide river. Meanwhile, using its Night Vision Goggles (NVG) and Infra Red (IR) sensors, the aircraft is able to spot a large group of improvised tactical vehicles in pursuit of the convoy. Since the group poses a significant threat to the convoy and the aircraft is already low on fuel, the convoy commander requests and receives permission to have the aircraft destroy the bridge after the convoy has safely passed it, thereby halting the pursuit.

Finally, at midnight, the convoy reaches the FOB intact and begins unloading the much needed supplies.

The scenario will run in a region of Norway, as both the local terrain and the typical weather map well to the script. Based on geo-specific source data provided by the Norwegian government, a 40x40km terrain dataset will be served to all participating federates and services. Although the intention is to keep the SE as geo-specific as possible, a number of minor changes will be performed to the source road network to provide alignment with the scenario, e.g. changing the surfaces of mountain roads to unpaved to increase the detrimental effects of the weather on the road state.



Figure 7: The route of the scenario projected on the geo specific area of Norway, including the convoy detour.

As part of the experiment, the architecture and interfaces described in Section 2 will be partially implemented. It will build upon a number of existing systems which will be provided by participating nations contribute and several newly developed assets. Specifically there hree types of assets have been identified:

- Data servers serve (dynamic) terrain and weather data layers using standard formats and protocols from the GIS community.
- Services respond to specific queries (e.g. routing) or events (e.g. weapon effects) and are accessible to all clients, thereby ensuring fair fight conditions and correlation.
- Simulations such as CGFs and human-in-the-loop systems act as clients that consume and interact with the dynamic SE data.

Within this distributed simulation, federate simulation entities will exchange data using HLA, while the state of terrain and feature data will be communicated using a combination of OGC web-standards and custom HLA FOMs (see Section 2.3).

Figure 8 shows the planned assets involved in the experiment. Note that each of the assets, even existing systems, will need to be modified to adhere to the interfaces of the proposed architecture and handle the messages and data regaring the dynamic state of the SE, i.e.

- Stealth: a 3D stealth viewer which will be used to get a visual overview of the events in the scenario and the dynamic effects that occur during its course;
- Lead vehicle: a human-in-the-loop desktop vehicle simulator that will be used to drive the convoy lead vehicle. The lead vehicle simulator will be used to have a human operator experience the effects of the dynamic changes to the road state and off-road trafficability due to the deteriorating weather conditions;
- CGF: a CGF tool will simulate the following vehicles in the convoy and all opposing forces. The CGF will be used to demonstrate how the dynamic changes in trafficability affect vehicle speeds;
- Fighter: a human-in-the-loop desktop fixed-wing simulator that will be used to provide air support for the convoy. The fighter simulator will be used to demonstrate the effects of dynamic weather on visual observations and sensor performance;
- Federate-terrain: a service that handles all dynamic effects on the SE originating from entities, for instance munition detonations impacting the terrain or an object such as a building or bridge. It is connected to the the HLA RTI to receive and process all relevant HLA interactions. For each received interaction, it requests the current local SE data and computes any changes in state (e.g. damage, deformation) and communicates any changes back to the terrain server;
- Trafficability: a service that computes upon request the local trafficability, given vehicle type(s) and a geographic location or route. For each request, it obtains the current local SE data (terrain surface state and road state), which might have changed by the Federate- and Weather-terrain services;
- Weather-terrain: a service that updates the SE state by simulating the effects of (dynamic) weather, in particular precipitation, on terrain and road surfaces (including infiltration and surface run-off). It receives changes in weather from the weather server, and updates the relevant SE data layers and communicates these back to the terrain server;
- Routing: a service that computes upon request the most efficient route to a given destination, taking into account the trafficability and road state;
- Atmosphere: a service that computes the additional attenuation that precipitation causes, based on the (dynamic) weather state. The resulting information can be used in a sensor model;

- Radar: a service that computes radar emissions and tracks based on HLA air and ground entities, and the information provided by the atmospheric effects service;
- Terrain service: stores the current state of all terrain layers of the SE (e.g. elevation, imagery, surface, vegetation, water bodies, infrastructure). Federates and interaction services can request layers, but also provide dynamic changes to layers. A notification mechanism informs all subscribers which data layers (and geographic bounds) have changed after each update;
- Weather service: stores the successive states of the dynamic weather during the scenario. Federates and interaction services can request weather data layers within a given geographic bound. A notification mechanism informs all subscribers when the weather state has changed.

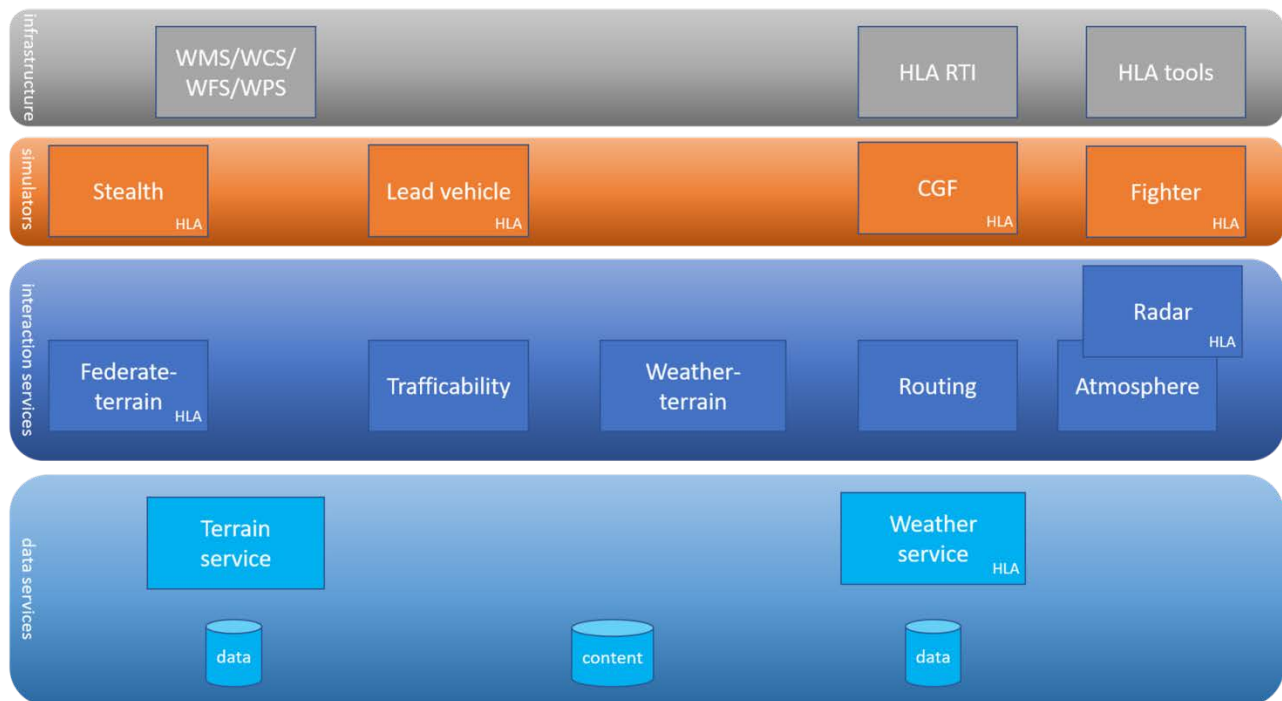


Figure 7: Overview of planned assets in the experiment

CONCLUSIONS

Discussion and Future work

The TG has just started preparing for the experimentation. The experiment will be performed in an incremental approach, where each increment will focus on specific services and interactions that are added. The aim of the experiment is to verify that the proposed solution approach works and to identify which areas of this approach need further work.

The lessons captured from the experimentation will be used by the TG to define recommendations on how future distributed simulation environments should be created so that a consistent, correlated and dynamic synthetic environment can be achieved among all participants. These recommendations will include:

- Advice on the M&S technologies and services that are needed to achieve a correlated representation of a dynamic SE.

- Advice on the best MTDS architecture that allows for the insertion of a dynamic SE.
- Identification of future standards and recommendations for the development of these.

The task group is planning to have this final report with recommendations ready by the end of 2020.

Summary

This paper first discussed the importance of have a realistic and correlated dynamic synthetic environment within future distributed simulation exercises, since a better representation of the dynamic conditions encountered in the real world will increase the value of such simulation environments. MSG-156 is studying how such a dynamic SE can be achieved. Using a number of concrete and compact Use Cases that require interactions within a dynamic SE, the TG will identify the requirements for such an environment and create conceptual modelling diagrams that illustrate how the various concepts that are involved are related to each other. Using this information an initial solution architecture has been created, which uses the MSaaS concept, to introduce terrain and weather information that can dynamically change during the running of the simulation.

Currently, MSG-156 is working on setting an experiment, where a number of assets from the participating countries are connected according to the solution architecture that has been created. With this experiment the taskgroup aims to check if the solution architecture is feasible and to derive more concrete requirements on the interfaces and standards used as well. In the MSG-156 final report these results will be used to inform recommendations on the architecture, methodologies, technologies and standards that are needed to achieve a dynamic correlated SE in the future.

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Exploiting Virtual Reality Technology in Support of Collective Training for the British Army

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ABSTRACT

The British Army's Collective Training Transformation Programme (CTTP) is seeking collective training that is conducted in more dynamic and complex environments (physical, virtual and cognitive). It is developing a Future Collective Training System (FCTS) which includes the aim by 2023 to deploy high fidelity simulation across all Army locations. Pilot studies have been initiated, including an investigation of Virtual Reality (VR) technology. Supported by the UK MoD's Defence Innovation Fund, Bohemia Interactive Simulations (BISim) were selected in December 2018 to conduct an FCTS pilot study into the use of Virtual Reality (VR) in Collective Training to explore the strengths, weaknesses, opportunities, and threats of VR technology and its employment. Over a 3-month period, the pilot considered the effectiveness, fidelity, practicality, architecture, scale, interoperability, infrastructure and mobility of VR. The pilot increased in scale and complexity culminating in 37 players in VR conducting training in a combined arms battle. It also investigated Mixed Reality (MR), cloud technology and training measurement and evaluation. The VR technology showed significant potential in support of collective training and conclusions and recommendations from the pilot are presented including those from the spiral development process.

1.0 INTRODUCTION

1.1 UK Land Collective Training

The British Army (Army) is seeking to modernise its collective training to deliver an effective and efficient combat-ready Army, optimised to meet the challenges of the evolving operating environment. This training modernisation will be through the Future Collective Training System (FCTS) being delivered by the Collective Training Transformation Programme (CTTP). The challenge is to produce a collective training environment that emulates the complexity, sophistication and sometimes disorder of the dynamic operating context and is also adaptable to reflect the changing threat and adversary capabilities. FCTS will make greater use of virtual training with a paradigm shift to 'virtual before live', where live training is used to consolidate and confirm skills learned in a virtual environment. All training will be instrumented, recorded, analysed and exploited.

Simulation and instrumentation systems will routinely be held and operated at unit level. The complexity of the contemporary operating environment will be represented by a Synthetic Operating Environment (SOE) which is coherent across the live, virtual and constructive environments.

1.2 The Potential of VR

For the past 20+ years, the training and simulation community has attempted to leverage commercial VR technologies but problems with helmet mounted display devices (HMDs) having insufficient resolution and field of view, excessive weight, and latencies and lag that can lead to simulator sickness. In some use cases the interaction with the virtual environment while “goggled in” is an ongoing challenge. However, the investment, pace of technology development and availability of VR has increased dramatically over the last 10 years and has seen VR migrate from the entertainment sector into many other different industries to be used for training and operational support. VR together with Augmented Reality (AR) and Mixed Reality (MR) have been identified as having the potential to provide better realism and immersion over what exists in desktop training and part-task trainers now, while at the same time reducing live training costs without compromising training experience. There are many examples of the latest VR technology being tested and trialled for training, for example for fast jet pilots, but less so in a collective training (CT) context. Nevertheless, VR technologies have significant potential to enhance land CT as they can increasingly provide high levels of immersion at relatively low cost and with a small physical footprint.

To explore the potential of VR and related technologies in land CT, the Army launched a competition in October 2018 to find a member of industry to lead the Virtual Reality in Land Training (VRLT) pilot study to take place in Q1 2019. In December 2018, Bohemia Interactive Simulations (UK) Limited (BISim) was awarded the contract to lead the VRLT pilot. The delivery of this pilot study commenced in December 2018 and was completed in April 2019 concluding with 37 players in VR.

2.0 AIM AND OBJECTIVES OF THE VRLT

The aim of the VRLT Pilot was “to identify the opportunities that Virtual Reality (VR) technology offers the Future Collective training System (FCTS)”. Supporting this aim, the VRLT was to explore the strengths, weaknesses, opportunities and threats (SWOT) of VR technology and its application to Army CT, with a focus on the development of leadership, situation awareness, decision-making, communication and co-operation. Further, the UK Defence Innovation Unit funded the VRLT Pilot with a desire to disrupt the traditional acquisition system, directly work with industry to put technology innovation in the hands of the user.

3.0 DESIGN OF VRLT PILOT AND TECHNICAL INNOVATIONS

3.1 VRLT Pilot Approach

The Army required an agile, spiral development approach to the VRLT Pilot exploring capability through a series of ‘Sprints’. Three sprints were agreed, each of which culminated in a technology demonstration within a one-week exercise. This provided an opportunity to integrate and evaluate progressively more complex technical innovations in the hands of the Army user, all within a formal training context. The baseline VR technology was the Oculus Rift with the virtual world generated by the UK’s Defence Virtual Simulation (DVS) based on Bohemia Interactive Simulations’ (BISim) VBS3 product. The 3 weekly Sprints were:

- Sprint 1 - “Crawl” – Building the foundation for innovation and testing the VR concept for Army CT for up to 18 users. This sprint baselined the use of VR capability, including demonstrating Oculus Rift and HTC Vive HMDs, a targeted high-fidelity grip controller; and automated After Action Review (AAR).

- Sprint 2 - “Walk” – A demonstration at scale with up to 37 users in VR including EXCON. The Sprint included emulation of the Battlespace Management System (BMS), Cloud Technologies, in-VR briefing and AAR and High-Fidelity Virtual Vehicle Interiors.
- Sprint 3 - “Run” – Building on the scale of Sprint 2 with further technological developments, including Mixed Reality, Customized Avatar; Voice and Infra-Red Analysis of User Challenge; and an Instrumented Live 105mm Light Gun.

3.2 VRLT Pilot Training Design

3.2.1 Training Scenario and Vignettes

To ensure that the Pilot technologies were evaluated within a training context, the Sprints were established as formal training events, with six serials (vignettes) that met a set of training objectives and assessed against the Army’s Collective Competency Objectives (CCOs). Each of the training serials consisted of a pre-briefing to the training audience, the exercise, data evaluation and after-action review. The training scenario itself was drawn from the US Army’s Decisive Action Training Environment (DATE) and included Armoured Infantry with up to 3 Warriors (3 crew and 6 dismounts for each vehicle) and one Challenger 2 (CR2) Armour vehicle (4 crew) together with supporting indirect fire and ISTAR. Common vignettes were used for all Sprints (Figure 3-1) and were scheduled to ensure that the training became progressively more challenging through each weekly Sprint (Table 3-1). The Experimentation period was used to evaluate alternative approaches to the training and test innovations, including: An opportunity for the training audience to “play the enemy”; remove the VR HMDs to rely solely on computer screens; train in the Combined Arms Tactical Trainer (CATT) (networked simulators with high physical fidelity).



Figure 3-1: VRLT Vignettes 1-6

Table 3-1: Typical Weekly VRLT Sprint Plan

	Monday	Tuesday	Wednesday	Thursday	Friday
AM	Intro & Equipment Familiarisation	V1 - Road Move	V3 - Clear Rural	V5 - Defend Urban	V6 - Patrol
PM	EXCON Familiarisation & Practice Game	V2 - Advance to Contact	V4 - Clear Urban	Experimentation	

3.2.2 Health and Safety

Training design and instructions to the training audience on health and safety of the VR equipment was based on guidance provided with the Oculus Rift and the HTC VIVE Pro. Players were advised to ‘lock’ their eyes at a fixed point while turning in the virtual world, close their eyes when the camera is not controlled by head movements, and minimise head movement. If feeling nauseous, they were required to notify staff and as necessary, remove their HMD. No players had to withdraw from training in VR. Typically, they would be immersed in the VR environment for 30-60 mins for each vignette. However, whilst no one was physically sick during the pilot with over 825 individual person hours in VR, there was the potential to feel queasy with prolonged use, particularly when not in full control of the motion. The high fidelity 3D Warrior interior was found to reduce nausea over the low fidelity 2D for the Warrior Crew used in Sprint 1.

3.2.3 VRLT Architecture

The VRLT architecture evolved as the Sprints were scaled up and new technologies and innovations were introduced. For Sprint 1 there was a single architecture based on DVS running on networked thick client PCs with a games Server. In Sprints 2 and 3 innovations such as the CR2, “Cloud-in-a-Box” and the 105mm Light Gun were linked to the DVS network through the Distributed Interactive Simulation (DIS) protocol. Figure 3-2 illustrates the Sprint 2 architecture.

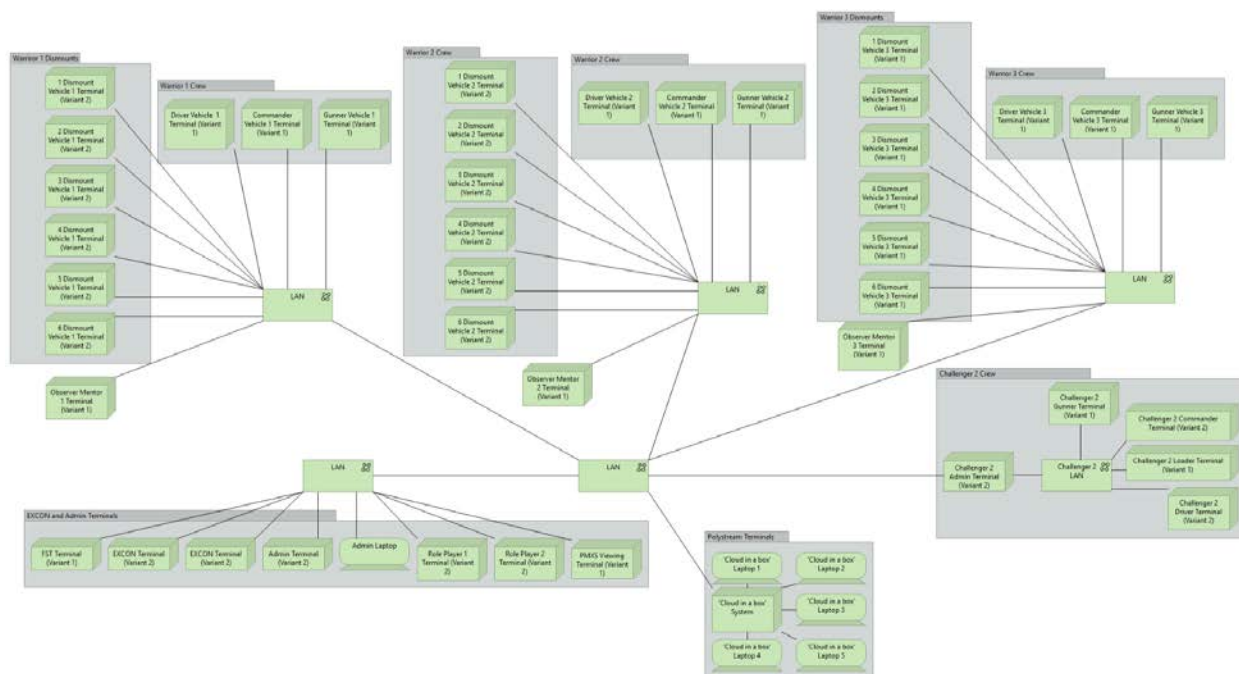


Figure 3-2: VRLT Sprint 2 Architecture

3.2.4 VRLT Infrastructure

The VRLT Pilot took place at Battlesbury Barracks, Warminster in one of the armoured vehicle garages. This provided an opportunity to test the deployability and ease of setting up quickly a training capability. The garage was also easily reconfigured and expanded as the Pilot progressed, including the introduction of a live instrumented 105mm Light Gun. The garage set up and configuration can be seen in Figures 3-2 and 3-3. Although each PC and associated equipment were for domestic use, the scale and characteristics of the total electrical load meant that the power had to be provided by a dedicated mobile power generator. This was

considered to be a special case given the nature of power supply to the garage. The other challenge of the garage was temperature control with a condensation risk to equipment in very cold weather.



Figure 3-2: CR2 (Left); EXCON (Centre Left); 3 x Warrior Crew & Dismounts (Right)



Figure 3-3: Warrior Configuration – 3x Crew (Right) – 6x Dismounts (Left/Centre)

3.3 VRLT Pilot Approach to Innovation

To stimulate innovation and pursue the most promising ideas for improving both VR and wider CT, technical innovations were collected and triaged throughout the Pilot. Innovation ideas were drawn from all the technical proposals, the Pilot Steering Group (PSG), the pilot contractors and the training audience and reviewed on their merits and evaluated for its opportunity cost by the PSG. To maximise the number of innovations being demonstrated, the pilot was established as an ‘Agile’ development with three sprints. This approach targeted the development effort on completing and demonstrating priority innovations, adding more only when these had been achieved. The innovations were delivered through a single customer-industry interface that enabled rapid and timely decision making with the prime contractor managing all the other industry subcontracts through an “innovation as a service” approach. The Agile approach allowed for high-risk / high-reward ideas, ideas to be generated late-on, and continual learning. The VRLT Pilot Technical Innovations and outcomes are described in Section 4.

3.4 Collection of VRLT Evidence and User Perspectives

The collection of evidence and user perspectives was drawn from structured interviews, e-voting and an Observer Mentor (OM) workshop. Structured Interviews were used in Sprint 1, and E-Voting, which was considered more effective, was used in Sprints 2 and 3. This evidence was typically collected immediately after the vignettes. An OM workshop was held to assess the benefit and achievability of the measurement and evaluation innovations. Analysis of the evidence is described in Section 5.

4.0 VRLT PILOT TECHNICAL COLLECTIVE TRAINING INNOVATIONS AND OUTCOMES

4.1 Sprint 1 Innovations

4.1.1 High Resolution VR Headsets

HTC VIVE Pro headsets with higher resolution and framerates were tested, however it was found that the Oculus Rift headsets were sufficient to provide a highly immersive environment for the training audience.

4.1.2 Proximity-Based Voice Communications

The voice communications used in Sprint 1 simulated the loudness of the voice based on the distance between speakers in the virtual world. As this was the cause of some confusion to the training audience it was decided to use SimSpeak in later Sprints.

4.1.3 Data Capture, Storage and Automated Intelligent Analysis Engine

The Cervus HIVE tool provided training data capture, storage and automated intelligent analysis. Taking data from a wide range of sources (eg. quantitative DVS/VBS3 data, qualitative observer/mentor (OM) data) it provided visualisations and infographic charts (Fig. 4.1) to support the AARs shortly after the training event itself (less than 60 minutes). The training audience quickly became familiar with the HIVE layout and when it was explained in context by the OMs, they could more easily interpret the training data being shown.



Figure 4-1: HIVE dashboard showing Metrics from a Warrior crew during a training Vignette

4.1.4 Untethered Headsets

Using wireless technology-based VR headsets (HTC VIVE Pro) eliminated the need for cables and allowed trainees to stand and move freely within a designated area. They were not found however, to improve the training experience of the seated dismounted trainees using tethered Oculus Rift HMDs and the technology was not used in this role again in later Sprints 2/3.

4.1.5 Assessing Development of Collective Knowledge, Skills and Attitudes (KSA)

The HIVE approach captured the training audience's self-assessment of their status before and after the training using tablet-based questionnaires with the aim of judging and reporting competency development. The purpose was to assess the development of collective knowledge, skills and attitudes (KSA) as indicators of leadership, situational awareness, decision making, communication and cooperation competencies. The value of this approach was limited by the errors in the data collected.

4.1.6 Use of Targeted Fidelity Grips

Warrior vehicle gunner station targeted fidelity grips were trialled to provide a realistic interaction for the trainee whilst still wearing the VR HMD (Fig. 4.2).



Figure 4-2: Warrior High Fidelity Gunner Controller with Trainee Using VR HMD (L) and Warrior Driver COTS Steering Wheel and Accelerator and Brake Foot Pedals (R)

When the Warrior gunner controls was not physically stable, calibrated or not as the real vehicle, the grips caused issues that prevented the users from conducting their roles and detracted from the CT. These issues were compounded by the VR which did not give the user feedback as they could not see the position of their hands. In these cases, the generic Xbox / keyboard interfaces were preferred for Sprint 2/3. In the case of the Warrior driver, the Commercial Off the Shelf (COTS) steering wheel, accelerator and brake foot pedals were more acceptable and were used through all Sprints (Figure 4.2).

4.2 Sprint 2 Innovations

4.2.1 2D/3D Battlespace Management System Emulation

Warrior and Challenger 2 Commanders were provided mission planning, situational awareness and blue force tracking through BISim's COTS Chalkboard Pro which is a tablet-based 2D/3D battlespace management

application. It did not accurately emulate the actual vehicles' BCIP (Bowman Infrastructure ComBAT and Platform) but it was found to be adequate for training in Sprints 2/3.

4.2.2 “Cloud in a Box” Simulation Hosting

With FCTS driving towards greater employability and access to simulation, Polystream's “Cloud in a Box” was trialled in Sprints 2/3. This solution has no downloads, installs or local data allowing over-the-network distributed or centralised training solutions. The processing servers are stored within a deployable ‘box’. During the VRLT demonstrations the technology ran 5 UAV stations with high fidelity graphics on inexpensive commercial business laptops. Due to the compressed timeframes for the pilot, the capability was not integrated with VR. The technology demonstrated the potential of a cloud-based, deployable service, where the footprint of the setup is not determined by the capability of the client machine graphics cards.

4.2.3 Use of VR in Pre-Training Briefing

VR technology was used to brief the plan and issue orders to the whole training audience via an avatar at the start of the training session. This had the potential to support distributed training events. However, the pre-briefing was of only a partial success as the limited behaviour and motion of the avatars and the lack of facial expression resulted in the only effective element of the communication being voice.

4.2.4 Use of VR In-Action by OMs

The VR environment offered the flexibility to enable an invisible observer to conduct inaction learning without disturbing the immersion of the wider training audience. However, the OMs preferred screens to the VR HMDs because the screens provided a wider field of view and could be more easily controlled without the risk of motion sickness. Further, the ability to provide coaching and mentoring during the exercise was limited in the same way as the prebriefing, with the only effective element of the communication being voice. However, with screens, the OMs were able to control their location and observe more than one area at once which meant that they began to change their way of working to focus on task or CCO specialism, such as use of firepower or exploitation of information and intelligence.

4.2.5 Use of VR the After-Action Review

VR HMDs were used to present replays and alternative perspectives to the training audience to illustrate and reinforce the learning points. Overlays and graphics were added to illustrate the After-Action Review, but these did not illustrate adequately the learning points and were hard for the training audience to interpret. The ability to provide after-action review during the exercise was limited in the same way as the pre-briefing, with the most effective element of the communication being voice.

4.2.6 “Play the Enemy”

DVS and the generic stations were rapidly re-configured (5 minutes) to allow Warrior crews to play the role of the enemy infantry fighting vehicle. This provided the training audience an opportunity, which was welcomed, to understand other force capabilities and limitations.

4.2.7 Automated Voice Analysis

Voice data was captured and passed to COTS voice to text software to transcribe the contents of the voice files, which combined meta-data from the audio file provided details of what was said, who said it, and the location that it was transmitted/received. The files were passed through the categorisation algorithm for content analysis and inclusion in the AAR. This allowed OMs to follow-up on cases of miscommunication or misunderstanding and particularly useful for larger exercises (Battlegroup and above).

4.2.8 High Fidelity Warrior Model

After feedback from Sprint 1, a new high fidelity internal and external model of the Warrior was developed and was successful in providing a much higher level of immersion and realism in the VR environment.

4.3 Sprint 3 Innovations

4.3.1 Mixed Reality

Mixed Reality (MR) technology was developed to enable the training audience to view their situational awareness application(s), whilst retaining VR immersion. This was achieved by taking a live webcam feed and rendering this in a set position in the DVS virtual world (Figure 4-3). This feed could be of the Battlespace Management System Emulation (on a tablet) or real maps or any video feed of value to the training audience. This allowed the training audience to interact with equipment and physical aids as they would normally, without the requirement to break their immersion. Without the appropriate situational awareness, the vehicle commander cannot effectively function. This innovation was seen as key to training collective competencies – situational awareness, decision making and cooperation.

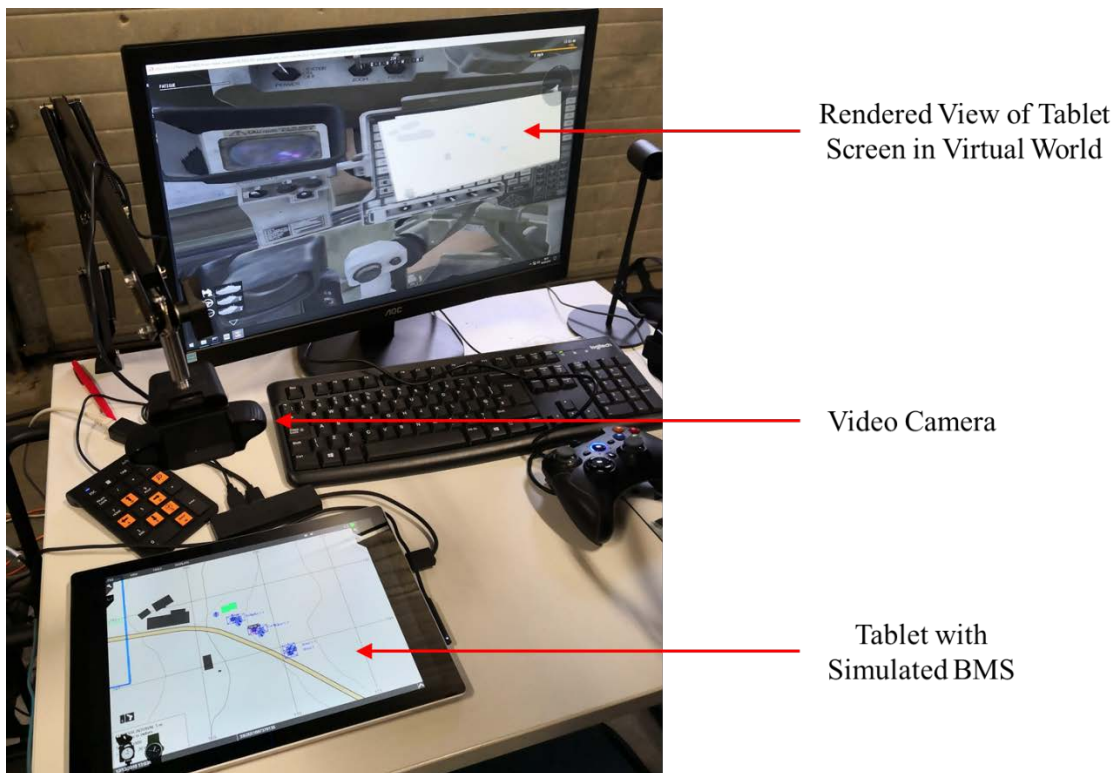


Figure 4-3: Mixed Reality with Real World Video Feed of Tablet Displayed Within the VR Simulation

4.3.2 Avatar Personalisation

Avatars in the simulation were personalised with realistic facial textures and features, height and Body Mass Index (BMI). The purpose was to allow individuals in the virtual world to recognise their colleagues. However, given the resolution of Oculus HMDs and obscuration of the avatar's face (helmet, chinstrap and goggles) the soldiers were not identifiable at ranges greater than about 20m in the virtual world. To enable

recognition of individuals, the overhead identifier was preserved throughout. Other characteristics such as gait and BMI were thought to be more beneficial to training.

4.3.3 HIVE/DVS Application Programming Interface (API)

Previously HIVE had taken data from DVS via the DIS protocol. The development of an open API enabled more advanced data analysis, which for VRLT were triggers showing when specific events occurred (eg. BLUE force crossing set lines) and OPFOR suppression detection.

4.3.4 Instrumented 105mm Light Gun

A live 105mm light gun was instrumented such that when fired with dummy rounds in the real world its effects were experienced in the virtual environment. This demonstrated the utility of blending live instrumented equipment and VR, enabling the gun crew to train procedural firing exercises whilst integrated with the broader VR-based training audience and higher command elements.

4.3.5 Communication Analysis and Workload Monitoring

An unobtrusive means of automatically capturing insights into the non-technical skills of communication and teamwork was introduced. The software collected communication data and produced a chart that showing factors contributing towards communication effectiveness providing an objective metric for communication that can be blended with other metrics to support the measurement of competency development within CT (Figure 4-4). Individual physiology measurements (temperature differential across the face) were also unobtrusively collected to assess the workload of an individual over time. This provided real-time feedback to the EXCON on the immediate response of the training audience to the cues and stimulus and challenge within the training scenario (Figure 4-4).



Figure 4-4: Communication Effectiveness Analysis (L) and Workload Monitoring (R)

4.3.6 VR Out of the Hatch

A helmet-mounted VR HMD was introduced that could be worn and easily removed (Figure 3-6). This allowed the participant to engage/disengage the VR headset during training to easily switch between VR, for example looking out of the armoured vehicle hatch, and real-world equipment such as situational awareness tablets and high-fidelity controls. This provided a simple inexpensive way to introduce mixed reality.



Figure 4-6: VR HMD that can be Easily Engaged/Disengaged

4.3.7 Challenger 2 (CR2) Gunner Loader

The CR2 Gunner was able to practice the procedural element of loading the CR2 round and charge from the box into the breech in a Unity-based virtual world within the overall DVS simulation. This innovation was seen to be useful to practice the loader procedure. However, it was not seen as necessary for training collective competencies.

4.3.8 Assessing Execute Against the Plan

The actual training audience's actions were compared with a constructive simulation or previous exercise data. This technique was thought by OMs to have most merit when observing larger exercises.

4.3.9 In-VR ROC Drill

The training audience were immersed in a scaled down virtual environment during the ROC (Rehearsal of Concepts) drill, ensuring a shared understanding of the plan. This showed that VR could be used in the preparatory part of the overall training process.



Figure 4-7: In-VR ROC Drill Within a Scaled Down Environment Model

4.4 Ranked Innovations

The innovations were reviewed and ranked by a group of stakeholders put into three tiers:

Table 4-1: VRLT Ranked Innovations

Tier 1	Tier 2	Tier 3
Classed as most beneficial to all arms sub-unit group training	Classed as beneficial but not a priority	Classed as not beneficial but could have wider benefits
* High Fidelity Model * Mixed reality * VR Out of the Hatch * High resolution VR headsets * Physiology/Voice Analysis * HIVE Training Data Analysis * Instrumented 105mm Lt Gun * Play the enemy	* Assessing Execute against Plan * Training from cloud in a * VR in action review * VR in AAR * VR pre-action brief * VR ROC drill * KSA Assessment	* Targetted Fidelity Grips * Untethered HMDs * Avatar Customisation * CR2 Gunner loader

5.0 ANALYSIS

5.1 Strengths, Weaknesses, Opportunities and Threats (SWOT) Analysis

An objective of the VRLT was to explore the Strengths, Weaknesses, Opportunities and Threats of VR in Army CT. The analysis was based on structured interviews, E-voting and workshops and the findings are in Table 5-1.

Table 5-1: VRLT VR SWOT Analysis Findings

Strengths	Weaknesses
• Can support significant numbers of trainees conducting CT in a large variety of scenarios • Communication and cooperation skills under pressure created through an immersive environment • High level of immersion reduces distractions from outside the virtual world • Situational awareness through manipulation of a range of aural and 3D visual cues • Easier to judge distance within virtual world than using the non-VR system • Decision making and judgements in a high-risk but 'safe to fail' environment • VR + MR supports training with situational awareness and battlespace management tools • Technology is highly versatile, reconfigurable, deployable, and cost effective	• Training skills where there is a need to develop physical psychomotor skills and the lack of haptic feedback and awareness of hand/body position limits the ability to train individual's physical coordination • Physical fitness as both tethered and untethered headsets offer a limited motion not supporting effective training of individual fitness • VR manufacturers' recommended time limits may reduce time in CT
Opportunities	Threats
• Cognitive procedural competencies can be trained where there is a need educate then	• The need to have a temperate environment to operate the VR headsets which mist up with

rapidly rehearse and repeatedly practice in a variety of scenarios, but physical psychomotor development is not required • Combined arms team working with dismounts operating alongside vehicles and other combined arms capabilities • Wider utility in education as well as training through demonstrating pre-briefing, ROC, briefing the plan, in-action review and AAR • Scale with ~40 users and ~100 deemed achievable • Flexibility to inject complexity and easily switch between configurations and scenarios • Deployability to point of need, with use of a location of opportunity with mobile power supply and network provision	condensation at low temperatures and sweat at high temperatures • The need to be aware of potential for VR sickness with use that does not conform to the manufacturer's guidelines

5.2 Findings Not Directly Related to VR/MR HMDs

The analysis also identified findings not directly related to VR but nevertheless of importance to training systems in general.

5.2.1 Communications

For participants to communicate they had to use training system voice nets. Users highlighted the differences between the way voice communication worked in the simulation and communications in the real-world. The dismounts were not able to tell when they could pass messages by voice (shouting). Participants also commented on the 'unrealism' of communications while using the Warrior vehicle intercom. The Command Net was perceived to be realistic. However, when Commanders were killed there was no way to transfer responsibility of their comms to the 2IC. Future deployments should add this functionality so that longer more complex scenarios can be exercised and be able to represent all forms of communications, i.e. face-to-face, live intercom and voice nets. This should include the ability for OMs to carry out 1-1 with individuals during training to reduce the break in immersion. For VR-based systems a button press for transmit would be preferred over a foot pedal whose position can be lost track of when in VR.

5.2.2 Simulation Artificial Intelligence (AI) Behaviour

In general, the behaviour of the enemy within the DVS simulation was deemed to be realistic. However, the CivPOP behaviour was viewed less favourably as it was sometimes difficult to distinguish between normal and abnormal behaviour, the implication being that it was difficult for the training audience to identify relevant indicators and cues to drive their behaviour. The issue may be more relevant for civilians because of the likely nuance/subtlety of cues (such as observing friendly forces) compared to the more obvious cues generated by the enemy (movement and fire is easier to recognise). For example, civilian-attired threats (so-called 'Dickers') appeared differently to the rest and hence, were easily identified.

5.3 Costs

A single unit of the VR set up was approximately £3000, which suggests for a deployable and configurable system it is a cost-effective approach to support cost effective training. This does not include other costs such as staff, maintenance and infrastructure although these would be applicable for any training system.

6.0 CONCLUSIONS

6.1 VR Technology Related Conclusions

- 6.1.1 VR can provide greater levels of immersion than using a screen-based virtual simulation because the training audience have a stereoscopic display to infer visual depth, stereo sound and can be less distracted as they cannot see or hear anything external to the simulation. They are not viewing the virtual world, they are in it.
- 6.1.2 VR has been successfully piloted in accordance with the manufacturers' guidelines on usage. Whilst a minority of the training audience did experience slight nausea on first use of the equipment, no one was physically sick and did not report any lasting side effects from partaking in the pilot.
- 6.1.3 Operation of up to circa 40 users in VR has been proven and scaling to 100 VR users is considered readily achievable, albeit with performance and stability risk with greater numbers of federated / dispersed users. Integrating simulation capabilities using open APIs directly, rather than DIS/HLA offer the potential to achieve higher system performance.
- 6.1.4 VR technology together with training system automation tools offer training at the point of need and flexibility to inject complexity, switch between training in alternative scenarios.
- 6.1.5 There are benefits in training dismounted team skills alongside fighting vehicles, using tethered VR and games console interfaces. The physical space requirements and safety constraints result in VR not being suitable for training untethered en-masse tactical dismounted activity.
- 6.1.6 VR can be used for conducting pre-briefing, ROC, briefing the plan, in action review and AAR but using screen-based systems also will remain necessary.
- 6.1.7 MR in concert with VR offers an approach to accessing battlespace management applications and situational awareness tools to train situational awareness competencies.
- 6.1.8 DVS (VBS3) is capable of supporting a VR CT environment.

6.2 Other Training and Technology Conclusions

- 6.2.1 To train team skills (i.e. – cooperation, communication, situational awareness, decision making and leadership) in a task context, it is necessary:
 - a. To be able to enact the tasks with realistic behaviours and high visual fidelity 3D virtual models. Lack of realism appears to distract the training audience and can lead to false training; and
 - b. To provide simulated communications and battlespace management applications that behave as they would in operations.
- 6.2.2 To deliver effective training, it is necessary to complement the VR-based training with observation and analysis package to understand:
 - a. The workload of the training audience;
 - b. The ability of the training audience to read the ground, perceive cues, indicators and warnings present in the training scenario; and
 - c. The ability of the training audience to comprehend the situation and make decisions.
- 6.2.3 Deployable cloud technologies and virtualisation of the graphics processing are in future expected to:
 - a. Reduce the acquisition cost of VR client machines by not requiring high end graphics cards;

- b. Improve the ergonomics of headsets with compute load transferred to the server; and
 - c. Reduce the costs of configuring training systems, with the simulation run from the server.
- 6.2.4 The agile, spiral development approach together with a culture of co-operation and continuous communication successfully put technology innovation in the hands of the Army user in only weeks from contract award. The industry “innovation as a service” approach also ensured an efficient customer/industry interface and the ability to rapidly introduce innovation into the Pilot.

7.0 RECOMMENDATIONS

- 7.1 VR should be considered for use in CT. It provides a more immersive environment than traditional 2D displays, creating a challenging environment to train teamwork, communication and coordination.
- 7.2 Further investigations should be undertaken to determine the physiological impact of being in VR for prolonged periods.
- 7.3 Targeted fidelity grips should be investigating further for use in a VR set up as they were not sufficiently user friendly, especially under the pressure of training.
- 7.4 Simulation application controls and schemas should be redesigned with a VR specific use-cases in mind to support natural and fluid control of virtual avatars and vehicles in the virtual environment.
- 7.5 When using VR, a suitable level of fidelity should be identified in terms of how rich the content of the simulation should be in addition to the behaviour of the entities and battlefield effects upon the virtual environment.
- 7.6 The fidelity of vehicle behaviours, vehicle 3D virtual models, and human behaviours are important to CT and should be researched and invested in to optimise training.
- 7.7 MR should be considered complementary to VR in a CT VR set up. Being able to use real world objects and natural actions (e.g. using a real world pen) enhances the training and user experience and negates the need to implement features in VR to compensate (e.g. a virtual pen).
- 7.8 A high priority should be placed on ensuring the emulation of the communications and battlespace management applications in CT is sufficiently representative.
- 7.9 Simulation interoperability standards should be re-evaluated for suitability in CT VR set ups. With increasing emphasis on VR for greater fidelity, realism, complexity, and how entities react and interact, standards such as DIS and HLA may not be appropriate in future. Alternatively, Open APIs may support improved interoperability, maximise innovation, flexibility and exploitation from the much larger non-defence VR markets.
- 7.10 More quantitative methods of performance measurement should be introduced into training. Non-intrusive performance measurement tools used in other industries should be brought into CT, eg. voice analysis and stress analysis using IR.
- 7.11 The agile, spiral development approach as demonstrated in the VRLT Pilot should be used to rapidly evaluate promising technologies in the hands of users.

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Project Hyper Real Immersion (HRI) - A Partnership Approach to the Development of a Mixed Reality (MR) Capability

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ABSTRACT

Technology used to provide military forces with their asymmetric advantage; however, the increasing pace of technological advances - particularly in adjacent markets in response to huge investments – is creating new challenges for global military forces. Procurement processes that have matured over decades are well suited to large complex equipment programmes, but are less well suited to exploiting technology, where the pace of change outpaces defence's ability to set requirements, go to competition, down-select, contract award, take delivery and finally get technology into service – by which time the technology is already outdated. In addition, training is a vital ingredient in converting equipment into relevant, credible capability. However, defence is not the market leader in simulation technology, and its procurement processes tend to drive industry to the cheapest compliant solution, rather than incentivising industry to capitalise on adjacent market advances to create a vibrant and evolving training eco-system.

The UK MOD is pioneering a fresh approach. Through the Defence and Security Accelerator initiative, it has down-selected Close Air Solutions (Project Hyper Real Immersion) and its Mixed Reality capability to be a vanguard project in a co-investment partnership approach to capability development. MOD believes that Project Hyper Real Immersion has the potential to transform the operational training landscape and provide our armed forces the ability to fight as we train– quite the opposite of what our peacetime training model provides today. Rather than waiting for a mature product to be available and then start a lengthy procurement process, leading to early obsolescence, MOD is exploring the benefits of a partnership approach, through rapid iterative development activity, to inform MOD's future requirements.

Project Hyper Real Immersion is thus exploring not only the potential technological benefits that MR might offer defence in the near future, but also whether a very different relationship with industry is required to capitalise on the technological revolution. This exciting Team UK approach to addressing future Modelling and Simulation requirements could have profound implications for the way modern military forces procure and develop capability; the UK MOD is very keen to collaborate with other nations facing the same challenge.

1.0 INTRODUCTION

The UK MOD – like many other military organisations – sees technology as its asymmetric advantage. However, the rapidly increasing pace of technological innovation, coupled with a procurement process better-suited to large complex programmes, has demanded a fresh approach. In addition, the large Original Equipment Manufacturers (OEMs) that dominate the defence market have extremely impressive latent capability; however, agility, dynamism and flexibility are more often the characteristics of the Small and Medium sized enterprises (SMEs) rather than large OEMs. The MOD is not the market leader in many of the technological areas that it wishes to exploit; adjacent markets – such as gaming, banking and wider

commerce – are investing £Bns to address wider market requirements, and thus defence risks being left in a technological “backwater”. As a result, MOD is looking at ways to engage with the technological revolution, leverage adjacent market investment, and re-define its relationship with national industry.

1.1 Equipment into Capability

Equipment endures as the essential foundation of military capability – the “Industrial Age” of warfare. Whilst equipment and kinetic effects will endure as core capabilities within a credible military arsenal, increasingly strategic success will be achieved by those best able to achieve decision agility and dominance – the “Information Age”. This new information environment has fundamental implications for Defence – for defining military capability, what it means to project military power, and how to ensure relevance in a fast-moving society in which the Military serves. Furthermore, as the late Sir Michael Quinlan, Permanent Secretary at the United Kingdom Ministry of Defence, observed:

‘In matters of military contingency, the expected, precisely because it is expected, is not to be expected. Rationale: what we expect, we plan and provide for; what we plan and provide for, we thereby deter; what we deter does not happen. What does happen is what we did not deter, because we did not plan and provide for it, because we did not expect it.’

Therefore, Defence need flexibility, adaptability and the ability to develop innovative ways to use existing equipment inventories in the most effective way possible. This demands a similarly agile, responsive and adaptable training system that can be swiftly reconfigured to address emerging threats. How does defence realise the full potential of its Equipment acquisitions and develop agile, responsive and credible military Capability?

The current paradigm is neither sustainable, nor affordable – a fresh approach is required. However, as Henry Ford famously observed, if you ask those closest to the problem to solve it, they will be limited by their own experience and imagination.

“If I had asked people what they wanted, they would have asked for faster horses” Henry Ford

This paper will review the way defence has traditionally engaged with synthetic training solutions, and with the tech industry, which form the foundation of defence’s legacy training solutions. The paper will then highlight the UK MOD’s fresh approach to the technology and training challenge, before providing an insight into its partnership approach to exploring the potential of Mixed Reality (MR) training solutions. Finally, the paper will look at some of the benefits of this pioneering approach, and the potential for international partners to collaborate to mutual benefit.

2.0 SYNTHETIC TRAINING

Despite the enduring aspiration to develop credible agile military capability, most simulators remain bespoke, with limited if any ability to network, leaving training focused primarily on single-platform essential skills. Furthermore, simulators are still viewed by some sections of the military as being a cheaper and less effective method of training – an option for those that cannot afford the “real thing”. Stove-piped simulation capability, which perpetuates the interoperability challenge, makes it very difficult and extremely expensive for the Armed Forces to train as they are going to fight. In addition, another challenge for simulation is isolation; modern warfighting is a team endeavour, so training in isolation creates major challenges for developing a successful teamwork approach, often addressed during live operations.

Defence has long recognised the benefits associated with training in the synthetic environment, which include enabling cost-effective, agile and responsive training with a risk and safety profile usually only

associated with live, high risk operational missions. However, legacy simulator training fails to replicate real-world conditions and dynamics – the participants are warm and dry in a geographically detached environment, and most simulators offer very stove-piped platform-centric training options. By contrast, modern military forces expect to be employed in dynamic and unpredictable scenarios, and in a Joint or Coalition environment; accordingly, operational training needs to be tailored accordingly. The MOD has recognised that MR offers significant potential to provide a highly challenging and dynamic training environment.

A prime example of where the training environment has failed to keep pace with the demands of the modern battlefield is Joint Terminal Attack Controller (JTAC) training. JTACs conduct some of the most dangerous and challenging tasks on the modern battlefield – co-ordinating joint fires in close proximity to friendly forces is a high-risk undertaking and requires comprehensive and effective training. The consequences of failure are not only unnecessary fatalities, but also potentially grave political impact that could have strategic consequences for the conflict. Peacetime safety constraints and risk appetite limit our ability to train effectively for such a scenario. As a result, we do the "best we can" with the resources available and expect our personnel to "learn on the job" when deployed on operational duties.

Indeed, the US has recognised formally this shortcoming between what technology (and simulators in particular) can provide and what is required, as follows:

"...the JTAC Simulator Accreditation Standard quickly became the build-to-standard, which was never intended. This resulted in a short-term increase in capability as programs had joint justification for funding to make improvements, however as time passed little effort was given to go beyond the JFS ESC standard. This has resulted in the stagnation of JTAC simulation capability."

Section B.3.2 - JTAC MOA

Technology has traditionally been the West's military asymmetric advantage; however, despite significant advances in adjacent market technology, defence has failed to capitalise fully. The military fields an impressive array of warfighting equipment, but training is the vital ingredient that converts Equipment into Capability. However, peacetime safety constraints coupled with omnipresent pressure on resources, limited training areas and a variety of other pressures, have left the military unable to train as it expects to fight. As a result, the military Trains Easy, and Fights Hard – which carries growing strategic reputational risks (of failure) and fails to exploit its huge investment in warfighting Equipment.

3.0 DEFENCE RELATIONSHIP WITH TECHNOLOGY

Globally, armed forces are struggling to adapt to the challenges and opportunities of the technological revolution. With traditional procurement processes matured to manage large complex equipment programmes, which are not well suited to exploit the rapidly changing world of technology. The challenge is to leverage the huge investments in adjacent markets (gaming, banking etc) and create a different relationship with industry to exploit the agility, innovation and exploitation that are core attributes of the technology industry.

If this is a challenge for individual nations, it is even more challenging for NATO where the strategic nature of the enterprise limits its ability to exploit innovation, pace and agility. The challenge therefore is how does the military embrace/exploit the wider technological revolution, to the mutual benefit of industry and defence.

By way of example, the UK MOD has invested significant resources in support of the UK Growth and Prosperity Agenda and the Defence and Security Accelerator (DASA) initiative. This aims to identify potentially "game-changing" technologies and co-invest with industry with the dual aim of Exploitation and

Commercialisation. Having enjoyed significant success with the Capability Proving initiative – the latest phase of the Innovation Challenge – MOD is now looking at ways to bridge the gap between the current Technology Readiness Level (TRL) – defined capability objectives and the final objective of benefits realisation, to secure value for money for both the UK government and Industry. However, as part of this process MOD has realised that in the fast-moving world of technology, the MOD’s procurement process fixes the level of technology early in the process, and thus risks fielded capability usually being dated at best, and at worst, obsolete.

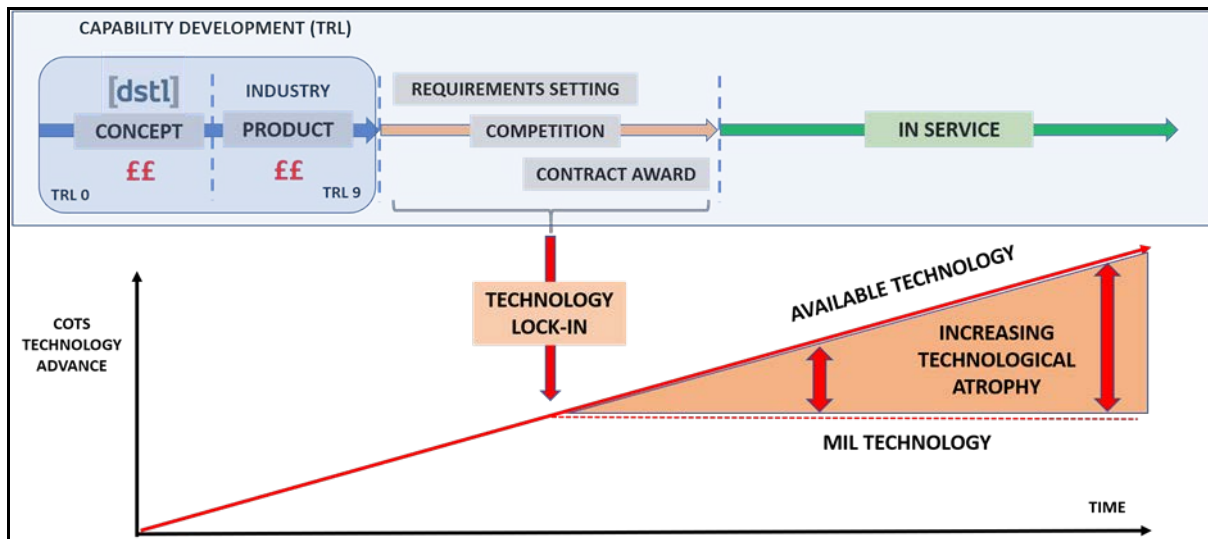


Figure 1 - Capability Development

The 2 primary challenges facing defence are thus:

- How to bridge the gap between the TRL7-defined outcome of the Capability Proving initiative and the point of Benefits realisation
- How to develop a different relationship with industry to exploit the technological revolution, to mutual benefit.

4.0 LEGACY DEFENCE TRAINING MODEL

Global defence forces have recognised the increasingly vital requirement to be able to operate high-technology equipment in a Joint and Coalition environment - the most likely scenario. However, security, agility, affordability, availability, peacetime safety appetite and air space restrictions all limit the ability to Train as you are going to Fight. Interoperability remains a challenge for defence, with equipment enduring as the essential foundation of military capability – the “Industrial Age” of warfare. In contrast, society has been swift to embrace the Information Age. Whilst equipment and kinetic effects will endure as core capabilities within a credible military arsenal, increasingly strategic success will be achieved by those best able to achieve decision agility and dominance. Society already embraces this philosophy, creating an increasing gulf between society’s expectation and the military’s capability.

Military Capability is a complex amalgam of several key components – Defence Lines of Development (DLODs¹) - only one of which is Equipment. Training has traditionally been focused on the live

¹ Training, Equipment, Personnel, Information, Concepts and Doctrine, Organisation, Infrastructure, Logistics with an overarching requirement for Interoperability

experience, using the equipment available in representative scenarios to breed confidence and competence in the equipment available. For many, this training is the most effective way to prepare for conflict, as it breeds familiarity with operational equipment and there remains a view that there is no substitute for “the real thing”. It remains challenging to replicate the fear, adrenalin and sense of jeopardy that the live experience provides, and although simulators have provided cost-effective ways to familiarise users with procedural standard operating procedures, and emergency procedures, simulators lack the immersive experience that is the bedrock of providing quality experiential-based training. Despite advances in simulation capability, defence has been slow to embrace the full potential of adjacent market advances in simulation technology. One reason that military leadership have been sceptical about exploiting technology is because a primary driver often appears to be financial – simulation training costs a fraction of live. Since the military leadership are ultimately accountable for operational capability, any compromise in the training DLOD would risk compromising operational capability, and thus lives. This has contributed to an eco-system where advances in technology are viewed with a degree of scepticism by senior leadership, and where many believe that simulation is only an option “for those that cannot afford the real thing”.

Warfare in the Information Age (WiA) will make fresh demands on our warfighters and will require very different skills and expertise. Next generation equipment will provide personnel with unparalleled levels of information but sifting out the nugget from the tsunami of information available will be challenging. In addition, this will create new challenges associated with tempo and ambiguity. The live training environment will always provide an end-to-end test of functional equipment capability; however, as its limitations grow, so it risks becoming an Achilles heel of modern military forces. Technology has been exploited in the military; however, rather than embracing technology through a partnership approach with industry, defence has tried to adapt its legacy procurement processes to this new technology revolution, which has led to a “rush to the bottom”, with the cheapest compliant solution being procured, rather than creating an eco-system where defence and industry work together to leverage adjacent market investments and advances to improve operational capability.

The legacy relationship between Defence and industry (Customer, Supplier) works well for established complex programmes, but is not well suited to capitalise on Technology. Technology is advancing apace, with new simulation technology including VR & AR demonstrating potential, but defence needs to establish a way to capitalise on the huge adjacent market investments by the gaming industry and others to create a dynamic new training eco-system for our military personnel and close the widening training gap between what can be achieved in peacetime and what is required at war.

Technology has traditionally been the West’s asymmetric advantage; however, is it fast becoming our liability?

5.0 A NEW APPROACH

The UK MOD has recognised that its legacy procurement model has been matured to focus on large, complex equipment programmes, and as a result is not ideally suited to the highly agile and dynamic world of technology. If defence is to create an eco-system that encourages innovation and proactively seeks more cost-effective ways to deliver operational capability, a fresh approach is required. Devised as a conduit for collaboration between industry, government defence and security departments, academia, and allies, the Defence and Security Accelerator (DASA) will allow the rapid development of innovative solutions to the most pressing security challenges.

5.1 Partnership

This UK initiative is looking at fresh ways in which to exploit agility, innovation and dynamism of the SME sector to address the technological challenges facing defence. As highlighted in the last UK Strategic

Project Hyper Real Immersion (HRI) - A Partnership Approach to the Development of a Mixed Reality (MR) Capability

Defence Review, the DASA initiative is not just looking at technology, but also the relationship between industry and the MOD. Instead of the traditional transactional relationship between customer and supplier, DASA is exploring the merits of a partnership approach to capability development, to see how adjacent markets investments in technology can be exploited to mutual benefit.

Close Air Solutions Ltd (CAS) is an example of a UK SME that has been supported by DASA to explore the potential of Mixed Reality via the Project Hyper Real Immersion (HRI) to transform the defence operational training landscape. CAS was selected from over 400 other SMEs in a competition to identify potential partners to develop new, innovative and transformative technological solutions to enduring defence challenges. This was not a science project – this was a co-investment partnership model designed to draw-through technology with a primary focus on Exploitation and Commercialisation. Both the MOD and CAS believed that the legacy simulation-based training model had failed to adequately exploit adjacent technological advances, and that Mixed Reality offered a pioneering way to improve dramatically the complexity, realism and value of training, and thus deliver more cost-effective and agile capability to the front-line.

The partnership with CAS has 3 main objectives:

- Save Lives
- Save Money
- Improve Operational Capability

These are ambitious aims; however, the partnership approach to capability development has already enabled focused investment, with both the user community and industry working closely together to develop a credible, relevant and agile solution.

6.0 HYPER REAL IMMERSION

The JTAC Use Case is a challenge for defence. Delivering dynamic effects in close proximity to friendly forces carries immense tactical and political risk due to the inherent dangers involved. However, the legacy training environment is becoming increasingly limited, and the gap between the training experience and that to be expected in conflict is broadening – at an alarming rate. Most challenging has been the steady divergence between the peacetime safety environment in which the military has to train, with society's attendant limited risk appetite, and the hostile, dangerous and high-risk demands of the operational environment. As a result, our warfighters rarely fight the way they have trained, and end up “learning on the job” when deployed on operations. This creates a real Duty of Care conundrum for politicians and senior leadership alike, and also explains why generations of military forces have commenced live military operations with extremely limited experience, suffered initial losses and only then started to develop credible warfighting experience and expertise.

6.1 Mixed Reality (MR)

Technology advances – particularly in the gaming industry – have created new opportunities for exploiting simulation as a training medium. However, the gaming industry objectives are very different to the military; the most effective operational training seeks to provide an immersive environment where the risks, fear, adrenaline and jeopardy of the anticipated operational environment can be replicated, to enable realistic and credible training to be conducted. Simulators have proven invaluable at training and testing JTAC procedures but are benign, isolated, unable to replicate conditions and complexity in a suitably realistic manner. As a result, there is an enduring requirement to conduct expensive – and ultimately extremely limited value – live training to meet prescribed training standards. These standards have become Input based – what proportion must be conducted Live and what can be done in a Simulator – rather than output-driven

based on the skills that must be demonstrated to meet the standard required. Both MOD and CAS believe that MR offers the potential to create a significantly more compelling training environment that will enable more effective, immersive and realistic training than legacy systems, enabling a more effective Day 1 capability (thus saving lives) and fulfilling our Duty of Care to our warfighters in a more cost-effective manner.

MR allows a user to concurrently exist in real and simulated worlds, with synthetic objects appearing alongside and interacting with real objects. For example, a virtual tank could appear on the real terrain, motion could produce virtual dust clouds, and the tank could be destroyed by either real or virtual detonations and drive behind and be occluded by a real building. This is considered an extension of augmented reality, where a level of immersion comparable to virtual reality is achieved in a live environment.

Exploitation of MR, or specifically, networked MR, is arguably the “innovation” in Modelling & Simulation that will support the greatest leap in preparedness throughout the next decade, however, this will not be without first overcoming some considerable technical challenges. The long term ‘dream’ of MR is perceived to be a small form factor wearable display (think Ballistic protection glasses). An exercise ‘player’ should be able to have MR artefacts / entities presented within their FOV and operate unencumbered by PC processing or network requirements. The enablers will not be developed at the National level as that would not offer value for money. Instead UK MOD intends to leverage adjacent technology from within the gaming / social media markets.

It's no secret Mark Zuckerberg is pinning Facebook's prospects on Augmented Reality (AR). For this vision to become reality, investment will run into \$B, Facebook will once again put itself into direct competition with Google, Microsoft & Apple. These and other consumer focused corporations will be reliant on low cost wearable AR displays - the same technology can and will be integrated into MR training solutions for military use. A clear indicator that no military will wish to develop bespoke solutions comes from the US - in November 18, Microsoft announced they had won a \$479 million contract to supply the US Army with a version of its HoloLens augmented reality headset – NATO should take note.

6.2 HRI Project

The goal of the HRI project is to provide a useful, User-centred, accredited, MR joint fires training capability demonstrator that has the potential, to provide more cost-effective training in the near future, and that informs the MOD's future requirements. During this phase the partnership will exploit rapid iterative development cycles to exploit technology through agility and innovation. The aim is to quickly develop an Operational Concept Demonstrator (OCD) that immediately offers value for defence. Through rapid iterative development and a partnership approach, the mixed reality capability can then be continuously evolved, to the maximum benefit of those invested.

The main limitation experienced during Project HRI early phases was the head tracking system. Position / pose tracking indoors with close-in synthetic scenes is starting to become well understood, however, the accuracy required to produce synthetic scenes of distances such as .5 to 5km are much higher due to the rules of sub-tension. The effect was that, over time, a misalignment of the synthetic scene with the physical environment occurred, which caused virtual objects to appear in the wrong places. The frequent recalibration required to correct this misalignment then proved to be intrusive to training. Given the points made previously about leveraging the gaming / social media sector, it would be inefficient to pursue mobile ‘on-the-man’ at this stage. Consequently, a different approach is now being adopted, one that lends itself to fixed Observation Points as a steppingstone to the desired end state of full ‘on-the-man’ capability. By focussing on the development of scientifically repeatable and efficient MR techniques and processes, as well as addressing other components of DLOD, such as a robust safety case and human factors, UK MOD intends to be in a position to exploit enabling technology when it becomes available. This approach will ultimately

reduce time to exploitation across the wide variety of potentially applicable use cases, as well as de-risking investment into MR technology.

By the end of the current project phase, HRI will have:

- Shown the MOD customer the way that MR technology can be incorporated as a military training capability to reduce the cost and increase the richness of joint fires training.
- Provided a US & NATO accredited OCD platform (based on existing simulation accreditation criteria), to deliver joint fires training in the live environment mixed with virtual content.
- A clear evidence-based Safety Case that covers the use of MR technology as a military training capability for joint fires
 - Vital if we are to understand the full implications of this new form of training
- A robust evidence based human centred design for the capability elements that identifies where this capability can add value to training.
 - Prepare the foundations to answer - is MR a more effective medium to conduct credible training than legacy simulation?
- A greater understanding of the technological pathways to optimising the facilitation of mixed reality training.
- The 3 primary technical areas of focus are as follows:
- Terrain: Aiming to rapidly gather and process extremely high-accuracy terrain data and ensure high-performance ingestion by simulation software.
 - This includes considering airborne and terrestrial data capture; integration with wide-area satellite terrain data; point classification (e.g. roads, vegetation, water, etc.); processing to simulation-compatible formats; and automation of the data processing pipeline.
- Software: Adapting and extending simulation software with optimisations for mixed reality,
 - To include highly accurate render masking, improved physics, and the ingestion of highly accurate terrain data.
- Advanced: Enablers for significant capability enhancements, particularly around the inclusion of physical objects in the synthetic environment,
 - Such as fast 3D scanning, real-time near-field tracking and object occlusion.

7.0 BENEFITS REALISATION

The UK MOD has been clear from the start that this is not a science project – the ambition for the project is exploitation, and to prevail the project must deliver tangible benefits, both near-term and into the future. The initial success of the initiative has resulted in several senior UK stakeholders identifying potential benefits from their investment in HRI, and an urgent need to exploit these benefits at the earliest opportunity. DASA had identified that Capability Pilots have the potential to be an effective mechanism to review the potential capability being developed to assess its viability, suitability and cost-effectiveness in a timely manner and enable an objective assessment of the potential benefits, both near and longer-term. They were also an opportunity to review an alternative to the TRL-based legacy procurement model, to one where there was immediate benefit to be gained from an early solution, and a clear roadmap for capability realisation through iterative development, exploiting commercial off-the-shelf technology and coherent adjacent Innovation Challenges.

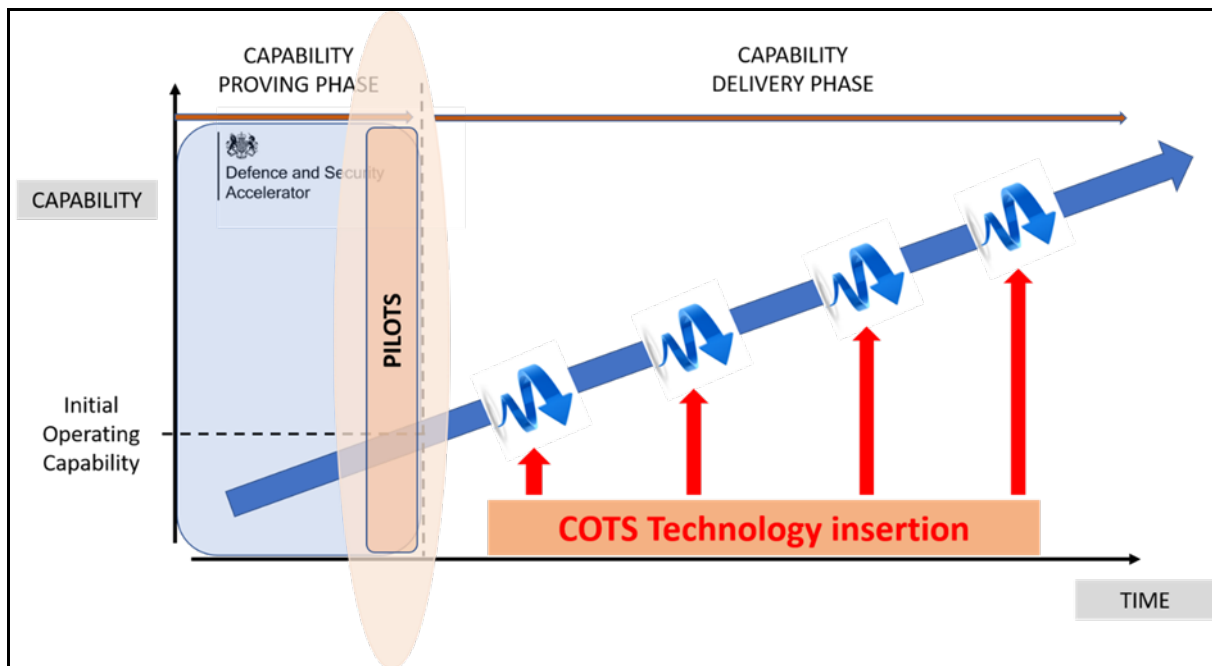


Figure 2 - Capability Pilot

The Capability Pilot activity would thus be the opportunity to review the potential benefits of the DASA investment to decide **if** and **when** to transition to a partnership delivery and exploitation approach.

7.1 Capability Pilots

The UK sees Capability Pilots as the optimum way to bridge from early capability demonstration into Benefits realisation. Unlike previous procurement models, where technology lock-in occurs early in the procurement process resulting in early obsolescence issues, the aim of the Capability Pilots is to decide whether a minimum viable capability is available which can provide immediate benefits, but which also has potential for iterative development to meet future needs. This assessment activity would explore the potential of a partnership approach to capability exploitation, to see whether there was a wider Commercial appetite/demand for the capability, thus creating the potential for MOD to exploit down-stream economies of scale. A Team UK approach to exploring wider export markets was enabled through the UK's Defence Growth Partnership initiative, working closely with the Defence Solutions Centre to establish whether any international partners were facing similar challenges as UK defence. This Team UK approach helped ensure that any MOD solution was also International by Design, to enable the core ambitions of Exploitation and Commercialisation to be achieved.

7.2 HRI Exploitation - JTAC Use Case

The UK MOD is looking to fund a JTAC HRI Capability Pilot to establish whether MR technology can achieve the following:

- Save Lives
- Save Money
- Improve Operational Effectiveness.

However, instead of waiting for technology to mature into a defined product, then start a procurement process, then run a competition, select a solution, contract and then build, test and accept, before entering service use - when the technology risks being obsolete having been overtaken by the next innovation in the market - MOD is seeking a fresh approach. The unique industry/MOD partnership expects the initial operating capability to lack the maturity required to deliver a full suite of benefits at Day 1; however, the Pilot will seek to establish whether the MR technology is sufficiently mature to provide a Minimum Viable Capability at Day 1, with significant immediate benefits for defence, and with the potential to liberate further benefits and features as adjacent market technological advances are made.

This pioneering approach has 2 main aims:

- Explore the potential of MR to transform the Operational Training landscape
- Better understand the benefits of a partnered approach to capability development

The MOD believes that HRI has the potential to provide a more effective training model for JTAC training, which will enable more realistic training, thus saving lives, improving operational capability, and delivered in a more cost-effective manner.

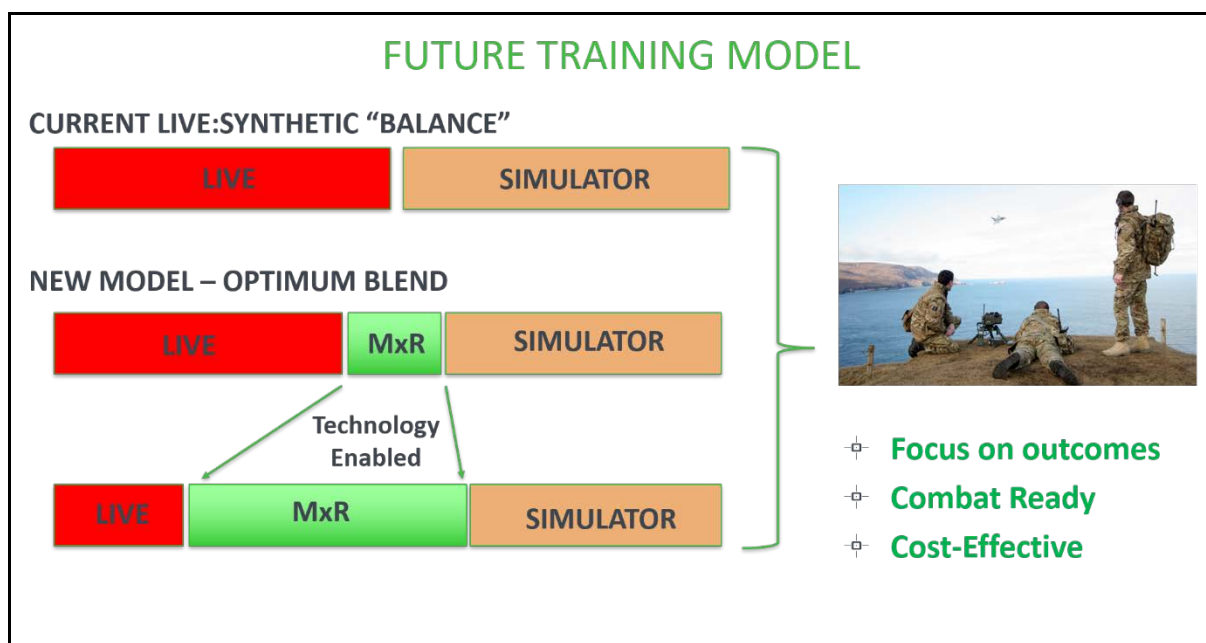


Figure 3 - Future Training Model

HRI is likely to offer more effective immersive training, closer to the real-world experience, and thus enable more credible, complex and high-risk missions to be used – Train HARD Fight EASY. MR is an exciting opportunity for defence, and it holds immense potential for the future. The key enablers for an “on the man” MR capability are already being developed by adjacent markets, where £Bns of investment are being made. However, MR can deliver benefits today – the MOD’s partnership with industry to develop HRI has already demonstrated where immediate benefits can be realised.

7.3 Partnerships

The challenge associated with exploiting the significant investment in, and capability of, the defence

equipment programme is not unique to the UK. Credible defence capability is not simply about equipment, yet in a society where the peacetime risk appetite is limited, and reducing, preparing our warfighters for conflict presents a significant challenge. The UK is exploring a fresh approach and is interested in developing this new model with international partners. HRI is a pathfinder project, which the UK MOD believes holds tremendous potential to deliver enduring benefit to the military. In addition, the MOD's partnership approach to capability development aims to change – perhaps fundamentally – defence's relationship with technology and associated industries, and to exploit adjacent market investment and technology to the benefit of defence.

8.0 CONCLUSION

Although Equipment is an important foundation of defence capability, WIA requires a cost-effective training eco-system to enable exploitation of next-generation equipment potential. Traditional defence industries are not market leaders in some of the adjacent markets where huge investments in related technological areas have fundamental implications for future defence capability. If defence is to achieve and maintain technological superiority over its potential adversaries, it needs to embrace the agility, innovation and pace of related technological advances. This requires a fresh approach to MOD's approach to capability:

- Defence Departments need a fresh approach to their relationships with industry to exploit the opportunities and agility that adjacent market investment will enable.
- Instead of waiting for technology to mature before starting the acquisition process, a partnership approach with tech industry could offer a significantly more cost-effective, agile and mutually beneficial outcome.

In the UK, Project HRI is a partnership approach to capability development between the UK MOD and Industry, with support from the UK Department for Trade and the Defence Growth Partnership, in a Team UK approach. The aim of the initiative is to explore the potential of MR to transform the operational training landscape with 3 main objectives:

- Save Lives
- Save Money
- Improve Operational Effectiveness.

HRI is a co-funded initiative which is enabling close collaboration between industry and the military, focused on a rapid iteration approach to capability development, and looking at fresh ways in which technology can be exploited - and swiftly – to provide more cost-effective and relevant capability. Ultimately, MOD expects HRI to migrate to an “on-the-man” capability; however, the technology to enable that is still some years away despite huge adjacent market investment. However, MOD also believes that there are other ways in which MR can offer near-term benefits through the HRI initiative and is working in close partnership with industry (and export partners) to capitalise fully on the potential that such technology might offer.



Immersive Simulation, Prototyping, and Evaluation of Infrared Sensor and Augmented Reality Technologies

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ABSTRACT

The U.S. Army CCDC C5ISR Center's Night Vision and Electronic Sensors Directorate (NVESD) is tasked with the development of low-light and infrared sensor technologies, which can range in form from air/vehicle mounted sensors, to infantry weapon sensors, and to head-mounted sensors and displays. In this paper, we discuss an immersive testing environment recently acquired by NVESD that is capable of virtual prototyping exercises for different sensor systems, and is likewise capable of serving as an immersive environment examining variations of AR displays and methods of presenting AR information to human operators. The immersive environment consists of a "green room," consisting of plexiglass panels that emit green light via controllable, electroluminescent tape. A pair of cameras, paired with a Vive virtual reality headset (HTC Corporation), are used to form a composite view of real objects and virtual overlays; any object observed in the immersive testing environment is visible to the user, but open green space is replaced by the virtual environment. We describe the new system and simulation use cases for both sensors and AR technologies, describing how such simulation technologies can allow for strict control of empirical scenarios, providing a vigorous evaluation of device characteristics. Ultimately, such simulations will allow Soldiers to experience sensor characteristics and AR displays before the first physical prototype is ever constructed, soliciting valuable user feedback early in the design phase of the acquisition lifecycle.

1.0 INTRODUCTION

One of the missions of the U.S. Army CCDC C5ISR Center's Night Vision and Electronic Sensor's Directorate (NVESD) involves evaluating, simulating, and modeling sensor performance, among many other tasks related to the development and acquisition of electro-optical and infrared sensors (EO/IR). In addition to measuring the optical properties of a sensor, such as sensor resolution, signal to noise ratio, and parallax error, evaluations of human performance with the sensors are also necessary for a comprehensive evaluation. Consequently, NVESD is continually working to improve methods of evaluating, modelling, and simulating human use of EO/IR sensors.

In this paper, we present a simulation tool recently acquired by NVESD, the gaps in our simulation capabilities

that it addresses, and its planned use cases. The tool, which we refer to as the Virtual Prototyping Holodeck (VPH), consists of simulation software, computers, virtual reality displays, cameras and sensors, and a physical environment. Collectively, these components allow users to be placed in a virtual environment. If desired, by utilizing visible cameras mounted to the VR headset, users can also see physical objects in the room while within the virtual environment. This enables NVESD's research team to conduct experiments at different points on the extended reality spectrum (ranging from entirely real to entirely virtual experiences), and experiments conducted with this simulation tool are best described as ranging from pure virtual reality (VR) to augmented VR (Azuma, 1997).

One key area of sensor simulation at NVESD, and a planned use case for the VPH, is developing virtual prototypes of EO/IR sensors. Virtual prototyping refers to the creation of a computer simulation of a product for presentation and evaluation (Wang, 2002). Building physical prototypes of a sensor is expensive, and it is a slow process compared to simulating a prototype of proposed or desired sensor specifications. Virtual prototyping, through simulation, can give decision makers and operators a chance to "try out" sensor designs before the first physical prototype is even constructed to better ensure that resources are spent on a solution that meets operational requirements. Virtual prototyping also enables operators to try out various proposed sensors or sensor configurations for a given operational task, and generates an opportunity for operators to provide feedback early in the design process. Objective performance on a task with the virtual prototype can even be measured through simulation.

The human factors or user experience (UX) literature has made it clear that the best approach to designing technology for human use often involves rapid, iterative prototyping (e.g., Nielsen, 1993; Jones & Richey, 2000). Rapid prototyping involves presenting early and progressive prototypes to users, and collecting user feedback and/or measuring performance repeatedly throughout the design cycle. In other words, users should be consulted early in the design process and should test progressive prototypes as soon as they become available so that iterative improvements can be made. This approach yields better results than waiting until a fully functional prototype is completed, produces improvements in usability faster and shortens the time needed to acquire a fully usable product, and ultimately generates cost savings over the product development cycle. Furthermore, in a military context, if user testing is deferred until after the product is already fully developed (from an engineering prospective), it may be too late to make substantial design changes.

Not only does this approach lead to greater cost savings, it leads to a better product. Scientists, engineers, and developers – while skilled in their respective disciplines – rarely have the same exact perspective of the intended user, despite their best intentions. Thus, there is always a need for tools that can facilitate user testing so sensors can be redesigned at a much earlier stage in the product development cycle. With such tools, users could give their feedback through a variety of methods such as cognitive think aloud protocols, performing simulations of real world tasks, surveys, interviews, and focus groups.

In summary, there is a broad need for immersive testing at NVESD. Currently, defining human performance with a sensor often involves presenting the visual imagery from the sensor on a computer monitor (Graybeal, Monfort, Du Bosq, & FAMILONI, 2018). In some applications, this may be exactly how the sensor's imagery will be displayed for a human operator (e.g., unmanned aerial system sensor feed displayed on a computer monitor). However, in other situations, the imagery will never be displayed on a computer monitor (e.g., imagery viewed through head-mounted sensors). Although we have observed very similar results between field trials and laboratory based perception tests using the same imagery collected in the field (e.g., Hixson, Teaney, May, Maurer, Nelson, & Pham, 2017; Hixson & Graybeal, 2018), the human use of the sensor may not be fully replicated when presenting users with a single static image. In other words, although humans perform similarly

when looking at a single image regardless of whether they are viewing it in the field versus in the laboratory, a static image may not represent the task well, such as with driving or route clearance visual tasks. In such cases, more immersive perceptual testing might derive better estimates of human performance.

The following sections present the design and capabilities of the newly acquired immersive simulation, intended use cases, and progress made towards those use cases.

2.0 SIMULATION APPARATUS AND METHODOLOGY

2.1 Virtual Prototyping Holodeck (VPH): Design and Construction

The immersive environment was designed by KRATOS Defense and Security Solutions using commercial “off the shelf” hardware and software components. The central purpose of the VPH is to provide immersive, mixed-reality experiences that are either entirely VR or are VR augmented with some real objects (i.e., augmented virtuality).

At the heart of the system is a “master” computer that controls all of the software for the simulations. Software components of the system include Steam VR, an image generator to render the visual imagery, a lighting controller for the immersive chamber, and an audio controller (for headset communication with those in the immersive chamber), among others. The first image generator software platform we used was Titan, but the system is designed to be compatible with any image generator so that simulations can be created using any software platforms.

This “master” computer connects wirelessly to “slave” wearable backpack computers (Hewlett Packard). A Vive VR display (HTC Corporation) connects directly to the backpack computer, and thus receives and displays imagery sent from the “master” computer. The system is also meant to be VR display agnostic, so that better displays can be incorporated as they become available, or so that different displays can be used, as determined by the specific requirements of a simulation and the strengths/weaknesses of various displays. Currently, two separate backpack and VR display pairs are linked to the “master” control computer, which enables two participants to use the VPH simultaneously. The two displays can run the same simulation simultaneously (i.e., users are placed in the same virtual environment) or the displays can be used separately to run two independent simulations.

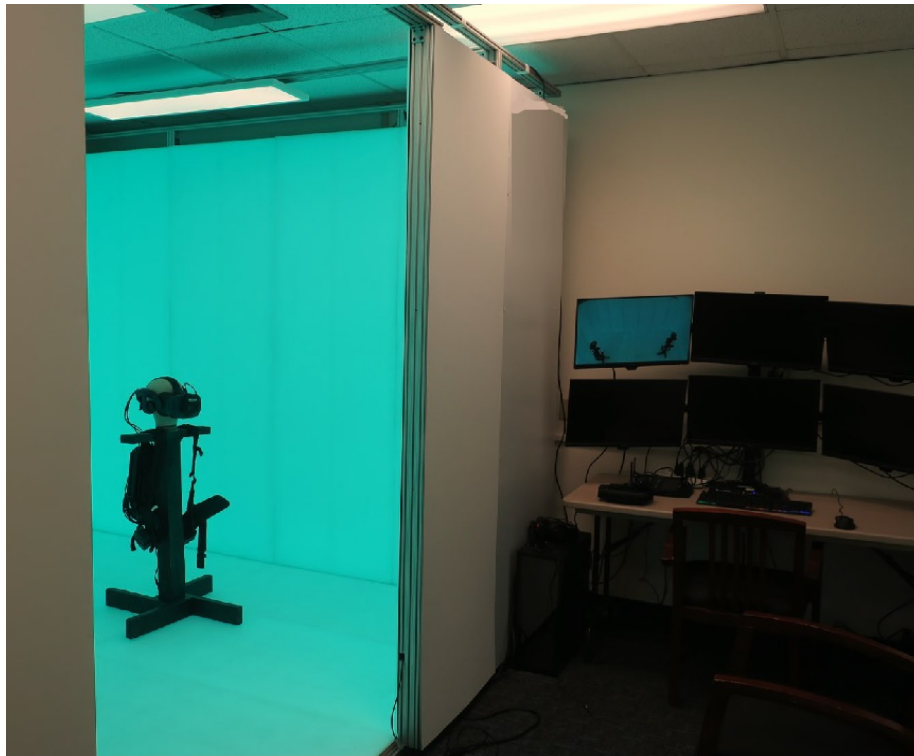


Figure 1: The NVESD Virtual Prototyping Holodeck (VPH). Participants enter the immersive simulation chamber through a permanent doorway in the walls of the 10 by 15 foot chamber (left). The research team controls the simulation through the master control suite (right).

The simulation chamber itself consists of plexiglass panels that emit green light via large strips of controllable, electroluminescent tape (see Figure 1). While this feature is unnecessary for pure VR experiments, lit panels provide constant illumination throughout the chamber (i.e., no shadows), and they provide a background that the system can use to merge VR environments with real objects, similar to the standard “green screen” technologies used in the film industry. A pair of cameras, custom mounted and integrated into the Vive display, are used to form a composite view of real objects and virtual overlays (see Figure 2); any object viewed by the cameras in the immersive testing environment is visible to the user, but open green space is replaced by the virtual environment (see Figure 3). To increase the user’s sense of immersion, a “virtual” wall and ceiling are each configured so that the user sees only the virtual environment when looking at the doorway or ceiling (i.e., in a direction where there are no green panels).

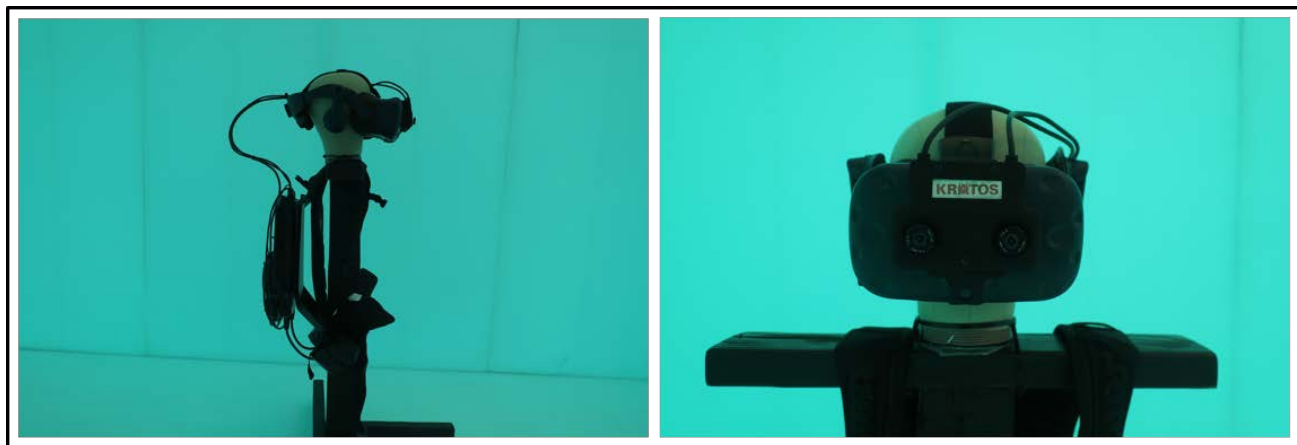


Figure 2: The wearable backpack computer system and the modified Vive display rest on a holding rack (left). A pair of cameras integrated into the Vive display enables the research team to display real objects in an otherwise virtual world (right).

Sensors mounted to the top of the chamber are used to track objects within it; Vive virtual reality system trackers (HTC Vive Corporation) are inexpensive tracking accessories that can be mounted to various objects, such as training rifles, sensor prototypes, and other objects that must interact with virtual environment. So far, the VPH has incorporated modified training rifles and a 3D-printed sensor prototype, which send wireless signals to the “master” computer (i.e., when a button or trigger is pressed), and the Vive virtual reality tracking system accessories allow this information regarding use of an object to be combined with three-dimensional orientation information about the object.



Figure 3: A soldier gives a hand signal inside the VPH immersive testing and simulation chamber (left). When viewed through the virtual reality display inside the VPH, the Soldier appears in the middle of a virtual environment (right).

2.2 Integration of the Night Vision Image Generator (NVIG) Software

One of the core system enhancements needed for our simulations was the integration of the Night Vision Image Generator (NVIG) software into the VPH. NVIG is a simulation tool developed by NVESD, capable of rendering scenes from the perspective of various visible and infrared sensors (Hixson, Miller, & May, 2015). In NVESD's Advanced Sensor Evaluation Facility, the optical properties of a sensor, such as blur, noise, and sampling, can be characterized and these measurements can be used to create a sensor profile in NVIG. Thus, the integration of NVIG into the VPH allowed us to immediately leverage our existing simulation capabilities. This work consisted of modifying NVIG to utilize the Steam VR Software Development Kit in order to display the NVIG imagery in the VPH's VR displays.

Additionally, NVIG had to be configured to support the atypical displays in the Vive DR displays. Many of our past simulations consisted of a single viewport in NVIG, and this single viewport was configured for displaying imagery on a standard computer monitor. However, because VR displays are much closer to the eyes, and because each eye is looking through a separate visual pathway (i.e., like binoculars), NVIG had to be configured to utilize two viewports, one for each eye, in a configuration that matched the pixel layout of the VR display. Figure 4 shows how a scene might be rendered in NVIG through two unique but overlapping viewports. Although the imagery presented to each eye is different, the human perceives a single uniform image with depth.

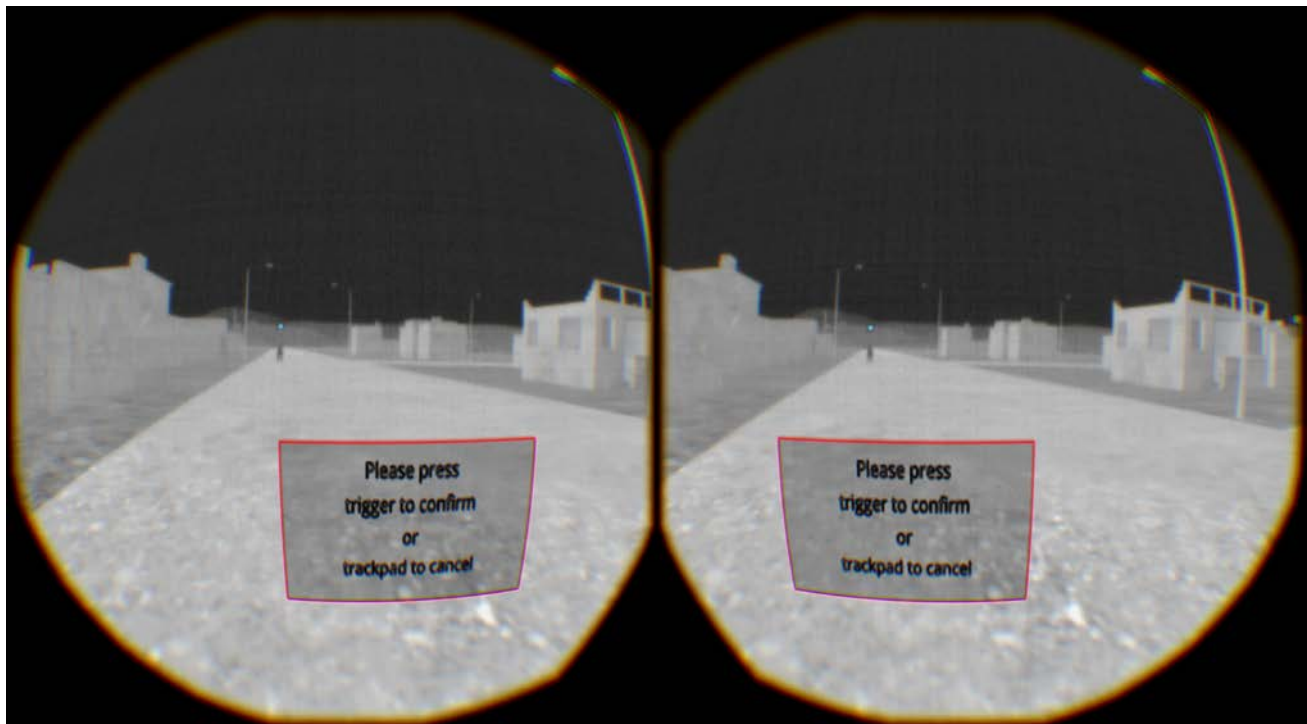


Figure 4: Example output from NVIG as it is configured to be displayed in the HTC Vive VR display. When pixels are mapped correctly, the stereo images are perceived by the participant as a single image within the VR display.

3.0 VIRTUAL PROTOTYPING APPLICATIONS AND PROGRESS

The U.S. Army strives to provide each Soldier with the right sensor to perform their assigned mission, taking performance along with size, weight, power, and cost (SWAP-C) into account. The Night Vision Integrated Performance Model (NV-IPM) is a system engineering tool that can be used to evaluate a wide variety of EO/IR systems (Teaney & Reynolds 2010). NV-IPM is commonly used to assess the performance of military target acquisition systems. The blur, noise, sampling, and contrast degradations from each component of the imaging system (target, background, atmosphere, optics, detector, electronics, display, etc.) are calculated by NV-IPM with a typical output of range performance. As each parameter within the model is changed, such as the size of the optics or the frame rate of the sensor, the range performance curve can change.

Typically, NV-IPM is used by system designers to determine the range performance curve of a proposed sensor. However, virtual prototyping allows a visual representation of the proposed sensor to be provided to the user without the time and expense of first building the sensor and performing a field collection. Virtual prototyping will also provide a visual representation of a proposed system during the analysis of alternatives and system design trade studies phases of development. This allows visualization differences of any sensor parameter (field-of-view, quantum efficiency, frame rate, optics diameter, etc.) to be quickly shown to the observer for a particular task and scene, or even a specific mission scenario. In addition, virtual prototyping can be used to test and evaluate both the optical properties of the sensor, as well as other elements of the technology, such as proposed display configurations for the human operator, including how various elements of AR symbology could be implemented. Conventional user research methods, such as heuristic analyses, user tests, surveys, interviews, and focus groups can also be facilitated by the VPH because it can provide context for the devices being developed, and can enable Soldiers to have hands-on interactions with many key aspects of the virtual prototype.

Overall, virtual prototyping, concept exploitation, and initial system integration executed early on in the design phase of imaging sensor system development reduces overall program cost, schedule, and performance risks. In the following sections, we discuss some specific applications for the VPH. We also discuss current goals, progress towards each application, and challenges experienced thus far.

3.1 Augmented Reality Simulations

One use of the VPH is to conduct simulations of augmented reality (AR) interfaces, as AR interfaces have become an increasingly important research topic at NVESD. The VPH is well suited to test how operator performance can change as a function of additional information provided to an operator during a given military task. The VPH can be used to both evaluate specific instances of technology (e.g., determining whether a proposed AR symbology layout will improve human performance, whether elements of an AR display are distracting, etc.), and also to understand human use of AR in broader contexts and generalizable experiments.

As we presented at last years' NATO MSG symposium, NVESD began an "AR Red Team" research program (Graybeal & Du Bosq, 2018). This was a collection of experiments designed to adapt our existing simulation capabilities into tools capable of simulating human performance with AR assistance. The initial AR Red Team experiments (Graybeal & Du Bosq, 2018) were focused on developing simulation capabilities to study target acquisition performance (Graybeal, Nguyen & Du Bosq, 2019), visual search (Monfort, Graybeal, de Visser, & Du Bosq 2018), vehicle identification performance (Graybeal, Nguyen & Du Bosq, 2019), and navigation with augmented reality assistance. Collectively, the results of these simulations demonstrated that the accuracy

thresholds required for AR systems to improve human performance vary as a function of both the specific task itself, and the difficulty of various perceptual judgements within the same task (*i.e.*, distant versus close targets).

Another lesson learned from these initial simulations was that having an accurate measurement of the baseline difficulty of the task is essential to deriving accurate assessments of human performance with AR, as all changes to human performance are calculated relative to baseline performance. The VPH represents a way to conduct similar experiments in a more immersive environment than using simple computer monitor displays. For some visual tasks, such as using an infantry weapon optic to search for a target, displaying still images on a monitor would not be the way a Soldier would naturally experience that imagery. In theory, an immersive test chamber could be used to give the Soldier control of a simulated sensor in the same way they could use a real sensor operationally. This may lead to both more accurate baseline assessments of performance for some tasks (*i.e.*, without AR assistance) and, consequently, better estimates of changes in performance due to AR assistance.

Our first planned augmented reality simulation in the VPH is an immersive target acquisition study. In contrast to using simulated sensor controls to search a scene for a designated target, the planned study will simply feature a VR display and a 360° virtual environment for participants to search in the VPH. This will enable us to more realistically simulate how a dismounted infantry Soldier would orient to a new AR target designation. We have successfully repurposed our existing target acquisition experimental structure in NVIG for use in the VPH, and we are working on developing an intuitive interface that enables participants to select and designate virtual entities. While our previous target acquisition simulations used a reticle in the center of the screen to designate targets (left), and the user rotated the screen's field of view with the sensor controls, this is not a good option for designating targets within head-mounted displays because orienting the head to point directly at a target can be difficult and uncomfortable. We are currently experimenting with giving the user a handheld wireless controller, which they can use to point at virtual entities, and while visually displaying the precise beam in NVIG (see Figure 5, left).

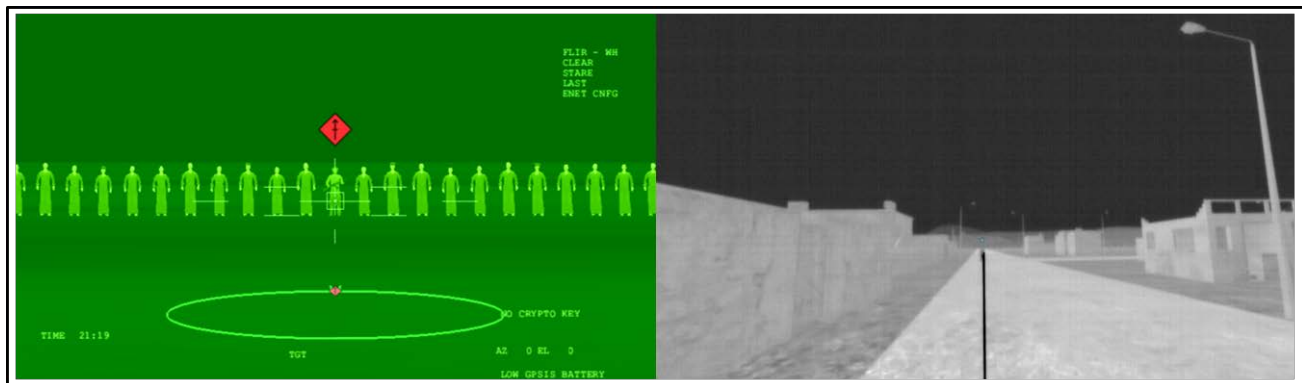


Figure 5: Human machine interface for target acquisition simulations. Our previous target acquisition task utilized a reticle at a fixed point in the center of the screen (right). We are developing ways to visualize the way a wireless controller is pointing into a virtual scene in the VPH (right). In the current VPH interface, a black beam radiates out from the users point of view towards the virtual entity being selected.

Another way we plan to utilize the VPH is to conduct simulations of various AR display symbology components and head-mounted displays (HMD). For example, a long term goal is to be able to ask sensor specific questions regarding optimal display symbology. Consider a situational awareness ring inserted into a warfighter's HMD

night-vision goggles. Various characteristics of the situational awareness ring, such as its optimal size, pitch (*i.e.*, viewing angle ranging from vertical to horizontal), the location of the ring within the display, etc., could be varied and used by participants to identify the best design layout. Compared to showing users pictures of display “mock-ups” and asking for feedback, the VPH will enable participants to utilize and “try-out” various AR display designs. This would enable the research team to collect higher quality subjective feedback and to even measure objective performance with the various display designs in immersive scenarios.

To this end, we have recently purchased eye-tracking devices (Pupil Labs), which are designed for integration into the HTC Vive displays in the VPH. These eye-tracking devices will enable us to record where participants are looking throughout the course of a simulation (gaze direction, dwell time, etc.). This will also enable us to identify if there are defects in a proposed AR display that are distracting, pulling an operator’s attention away from the field of regard at inappropriate times, and it will also enable us to assess information transfer efficiency. The best AR visual overlay is the one that provides all of the required information while minimally capturing the operator’s gaze (relative to the field of regard). In other words, even when using AR displays, operators should be focused on their field of regard, and eye-tracking simulations in the VPH will help us identify AR symbology layouts that transfer information without becoming overly distracting.

3.2 Perception Experiments and Simulations

Another use of the VPH is to conduct virtual, immersive perception testing. Perception testing at NVESD is typically focused on detection and identification tasks. Detection tasks require a person to perceive a target visual sensory event when it occurs, while identification tasks require a person to assign a categorical label (of varying specificity) to a perceived object (DiCarlo, Zoccolan, & Rust, 2012).

NVESD’s Perception Laboratory often assists with defining sensor requirements for a specific military task by showing real (or in some cases, simulated) imagery to human observers. This often involves showing sensor imagery that ranges in quality, enabling researchers to identify the minimal image quality needed in order to complete a given military task. In addition to defining sensor requirements, perception tests are conducted regularly at NVESD to understand displayed imagery in broader contexts, such as how range to the target, blur, sensor noise, and other variables affect detection and identification performance. Again, more operationally representative perception tests may eventually be possible when showing participants fixed imagery on a computer screen does not represent the task well. This may be especially true for cases when the human’s interaction with a sensor is critical to performance, as human use of a sensor can be simulated in the VPH.

Of the applications presented in this manuscript, immersive perception testing is perhaps the most challenging because the visual fidelity of the simulation is incredibly important to task performance. In contrast to augmented reality simulations, which can test how a human would interact with additional information provided during a task with a simple visual display, the performance during a perception task depends entirely on the visual fidelity of the imagery.

The integration of NVIG into the VPH is a substantial step towards this goal, as NVIG has been used previously to render high quality simulations of objects and object signatures (e.g., Graybeal, Nguyen & Du Bosq, Hixson et al., 2017; see Figure 6). Another NVESD experiment we are currently developing is designed to validate the visual representations being displayed in the VPH. The experiment will display images of basic shapes (e.g., triangles), and will ask participants to determine the orientation of the triangles (Bijl & Valetton 1998). The results from this study will be the first step towards confirming that targets being rendered in NVIG are appearing correctly in the VPH’s VR displays with an equivalent modelled task difficulty.

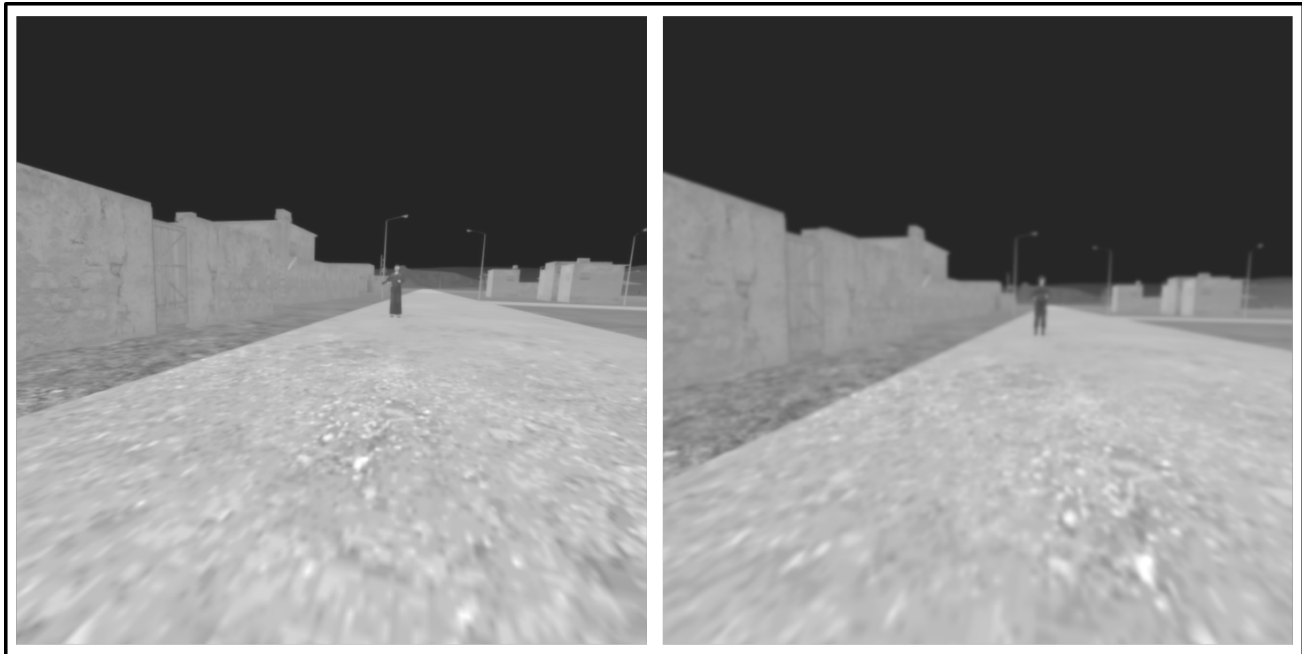


Figure 6: Example scenes from a perception task rendered by NVIG for display in the VPH. The task was designed to compare perceptual performance between an ideal sensor (left) and a lower quality sensor (right). Participants viewed virtual persons and attempted to determine whether each one was holding a weapon.

One challenge we have encountered is the correct modelling of the immersive VR display, which is much more complicated than a standard computer monitor. For example, pixel densities are uniform for a computer monitor but are not uniform for many VR displays, as they feature a higher density of pixels in the center of the display, with a lower density of pixels in the peripheral vision. Another challenge we encountered is the Vive's display resolution is low enough that some of our visual tasks would be "display limited," meaning that the perception test would not be able to accurately display some visual stimuli due to insufficient pixels on target. Therefore, the system will need to be upgraded in the future by improving the quality of the VR displays in order to successfully accomplish our goals for all of our various perception testing applications.

CONCLUSION

Immersive simulation has great potential to improve and expedite technology development because it can enable users to work with virtual prototypes long before a physical prototype becomes available. This allows user feedback and performance to be incorporated earlier in the iterative design process. In addition to general virtual prototyping, the VPH is well suited for simulations of AR displays and for immersive perception testing. This provides NVESD with new research mechanisms to understand EO/IR sensor performance, a tool to study digital augmentation of EO/IR sensors, and a method of conducting tests where the participant has greater control over the imagery being displayed (because they can interact with the immersive scenarios).

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2019 NATO MODELLING AND SIMULATION GROUP SYMPOSIUM

M&S as A Service (Msaas): Proof of Concept Development and Integration Of A Sensor-As-Service for A Virtual Flight Training Eurofighter Simulation

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ABSTRACT

The NATO Modelling and Simulation Group MSG-136 "Modelling and Simulation as a Service (MSaaS)" as well as the follow-on MSG-164 "M&S as a Service (MSaaS) Phase 2" targets to develop a service architecture providing rapid deployment of interoperable and credible simulation environments.

This paper presents the results of a proof of concept implementation of an optical and infrared sensor which is realized as a Sensor-as-a-Service. This Sensor-as-a-Service can be provided to other simulators or real operational systems as a lightweight service which can easily be deployed and hosted e.g. on a NATO cloud. As a use case the sensor-as-a-service was integrated into a flight training Eurofighter simulator of Airbus.

Through this proof of concept implementation it was investigated, how a sensor-as-a-service can be designed and hosted on a cloud system and be interconnected with a virtual flight training Eurofighter simulation.

A key issue in infrared image generation is to provide a virtual 3D terrain including multispectral information such as terrain surface types. In this proof of concept demonstration the OGC standard Common Data Base (CDB) was selected. Moving objects are received either through DIS/HLA distributed simulation networks or optionally passed through a service request to the sensor as a service. The sensor parameters like the spectrum, orientation or zoom level can be steered by the virtual Eurofighter cockpit through the service interface.

1.0 INTRODUCTION

Modelling and Simulation (M&S) is a key enabler for the delivery of capabilities to NATO and Nations in the domains of training, analysis and decision-making. M&S solutions have to be integrated seamlessly in future computer information systems capabilities to ensure increased efficiency, affordability, interoperability and reusability. NATO and the nations regularly use distributed simulation environments for various purposes

(e.g., training, mission rehearsal, or decision support in acquisition processes). Achieving interoperability between participating systems and ensuring credibility of results still require substantial effort with regards to time, personnel, and budget. There is a lack of simulation standards, agreements, and reference architectures that focus on higher levels of interoperability and simulation credibility, compared to the current standards like DIS (Distributive Interactive Simulation) or HLA (High Level Architecture), which mainly focus on technical, syntactic and – to a limited degree – on semantic interoperability.

The follow-on activities in MSG-164 will mature MSaaS from a lab environment to an operationally relevant environment and conduct necessary research and development efforts. Through close cooperation with the operational user community and participation in exercises, this activity contributes to realizing the MSaaS vision that “M&S products, data and processes are conveniently accessible and available on-demand to all users in order to enhance operational effectiveness” with the following objectives:

- advance and promote operational readiness of M&S as a Service;
- align national efforts and share national experience in establishing capabilities of M&S as a Service;
- investigate critical research and development topics to further enhance benefits from M&S as a Service.

This activity will establish a cloud-native demonstrator to support the M&S as a Service approach by including an exemplary flight simulator device (representing a real operational user interface) that connects to several national services, like computer generated forces service, sensor service as well as two weapon services. The conceptual vision is to offer a simulation environment that is easy to setup no matter in which network it’s used and the central provision of main functionalities which can be of interest for other systems or client.

2.0 DEMONSTRATOR CONCEPT AND ARCHITECTURE

2.1 Allied Framework for MSaaS

Figure 1 gives a high level overview of the Allied Framework for MSaaS as described in the MSG-136 Operational Concept Document (OCD) – see [3]:

The basic idea is to “servicize” the M&S components to Modelling-/Simulation Services (e.g. a computer generated forces service) or Data Services (e.g. a Synthetic Environment Service providing terrain data). In addition, there might be for management purposes Repository- and Registry Services as well as MSaaS Portal Services, to Discover, Compose and Execute Services within a MSaaS portal.

Those services may be hosted either in National clouds, a NATO cloud or in Mission & Coalition clouds. In addition, those clouds need to be accessible through legacy systems like Thin Clients, Simulations / Simulators and operational C2 (command and control) systems in order to provide those systems the necessary services.

Finally, the setup of the MSaaS environment is supported by the MSaaS Technical Reference Architecture and the MSaaS Process and Governance Policies.

The objective is to realise the MSaaS vision that M&S products, data and processes are conveniently accessible and available on demand to all users in order to enhance operational effectiveness.

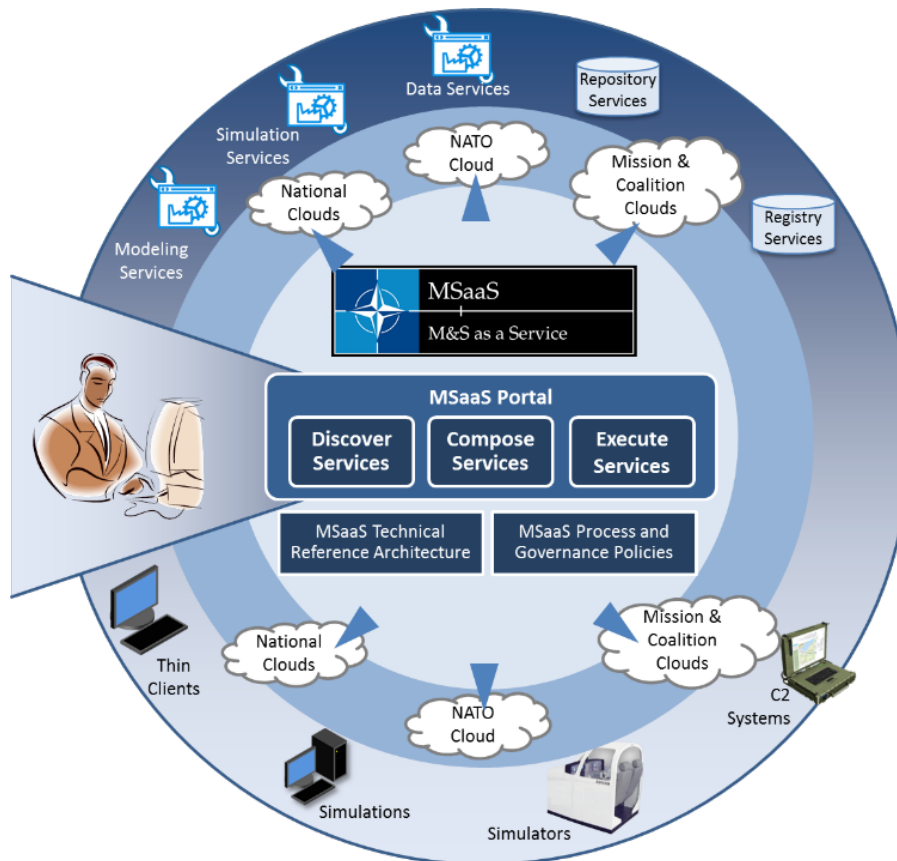


Figure 1: The Allied Framework for MSaaS

2.2 Demonstrator Concept

Based on the Allied Framework for MSaaS and the MSaaS Technical Reference [11], the German MSG-164 members designed a proof of concept demonstrator to evaluate the feasibility of parts of the MSaaS approach.

The proof of concept demonstrator should not be limited to one specific M&S application area, say, for training or for simulation-based analyses, but must show the general technical capabilities of a MSaaS system implementation. Each chosen system within the demonstrator in Figure 2 should represent a specific component of the architecture:

- Most units of all forces managed and distributed within the MSaaS service cloud are computer generated forces (GCF) simulated by a **CGF simulation service**. For this purpose, the German agent-based 3D simulation model PAXSEM from AIRBUS was selected. PAXSEM as a CGF service may run without user-interaction, as it can be controlled remotely through a web **simulation control application COP**.
- The **weapon effect service** (WES) is able to monitor a DIS/HLA federation in order to centrally compute weapon effects on simulation entities in order to help to solve fair-fight problems. As an extension, the **exterior weapon service** (EWS) is capable to be used to provide weapon models outside of a simulation. The service is capable to be used for ballistic weapons (e.g., artillery) as well as for unguided rockets and guided missiles.
- The **virtual sensor service** is capable of providing an optical (and infrared) view of an electro-optical sensor of simulated entity in HLA/DIS federation. The sensor orientation may be controlled through

a network protocol (currently through a proprietary network protocol of a GE camera vendor - future extendable through a REST API).

- A flight training simulation including a **virtual cockpit** is representing a Eurofighter system that is publishing its own entity into the service cloud.



Figure 2: Concept overview of the Proof-of-Concept Demonstrator

3.0 DEMONSTRATOR COMPONENTS AND IMPLEMENTATION

In order to connect the demonstrator components, two buses are foreseen: Simulation bus and Service bus. The simulation bus puts up a standard DIS communication protocol, using a standard object model (Real-time Platform-level Reference (RPR v2) - based) to exchange data between the services. For cases, when the services need an extended or custom communication channel, the service bus is introduced providing a REST interface.

3.1 PAXSEM CGF Service

The CGF service is realized through the agent-based simulation framework PAXSEM for technical & tactical simulation of operational scenarios. PAXSEM has been developed by AIRBUS on behalf of the German Armed Forces since 2008 and has already provided a proof of concept when applied in several simulation based analyses involving the method Data Farming as well as a scenario generator in distributed environments such as the German system demonstrator VIntEL (see [6][7]).

PAXSEM engages so called agents, who interact in virtual scenarios. These agents independently execute activities, perceive their environment (sensors), intervene therein (effectors) and react upon the changes in the respective ambience (dynamics). This way, multiple differential decision alternatives are created describing a wide sample space. The mutual interference of individual agents allows courses of simulation that are often impossible to predict and uniquely confined by the agents' abilities. PAXSEM is applied in two following mode of simulation.

PAXSEM as a scenario driver within a networked simulation environment: Here, PAXSEM feeds in data in real-time into a distributed simulation environment and is a peer federate to other virtual and real systems

connected. Besides training such testbeds enable to do conceptual examinations whose real-world execution would be difficult (consumption of scarce resources) or even impossible (safety regulations, systems to be developed).

Among its multiple standards PAXSEM comes with standardized interfaces which allow its flexible integration in heterogeneous testbeds or other experimental activities. Through the interfaces PAXSEM can generate a wider operational picture when CGF provide a simple stimulus or dynamic interaction to other simulators or real systems connected. Therefore PAXSEM has a built-in C2-Sim Gateway module which is able to feed C2 systems through standards, such as C-BML, STANAG 5527 conform NFFI and a range of other standardized formats. PAXSEM can feed tailored scenarios into compatible simulators (e.g., through DIS or HLA [4]) e.g., for training or analyses.

3.2 Weapon Services

3.2.1 Weapon Effect Service

The WES is the central component in a distributed environment that computes the weapon effect on simulation entities on the basis of a munition detonation (see Figure 3). Thus, the service evaluates the geographic position of the munition detonation and calculates the resulting direct and indirect (coverage by other entities considered) damage state of the requesting simulation (target) entity. In the follow up, the calculation result is published back to the distributed environment on basis of a weapon effect.

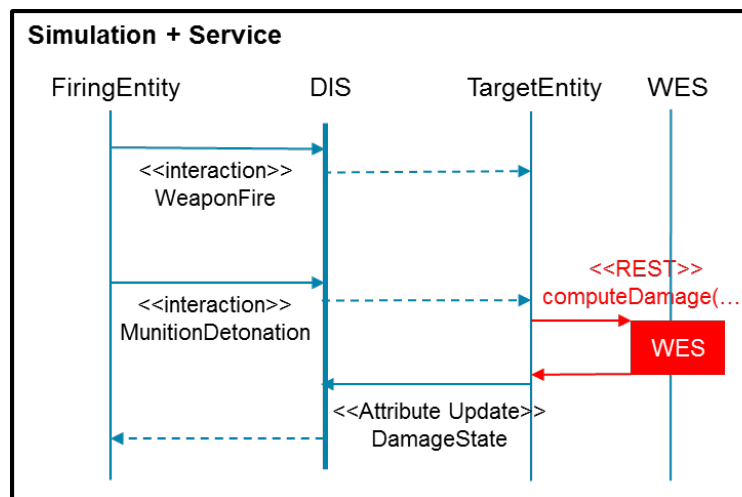


Figure 3: Communication model in context of a weapon effect

3.2.2 Exterior Weapon Service

The EWS simulates, in addition to the WES, the whole process of weapon fire, missile creation throughout the munition detonation (see Figure 4). Depending on the missile model, the missile flight is calculated and published back continuously (including attribute updates, e.g., spatial position) to the distribution environment. As soon as the flight model calculates the munition detonation, the corresponding interaction is sent back to the distributed environment.

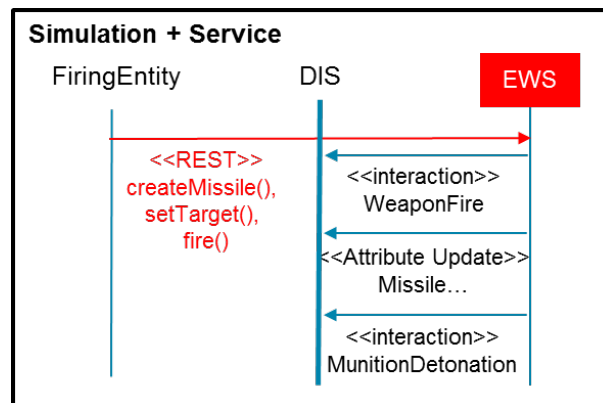


Figure 4: Communication model in context of aiming and firing

3.3 Virtual Sensor Service

The Virtual Sensor Service is a component in a distributed environment that enables to attach a virtual sensor to an entity of interest and to stream that specific camera view to the requestor (see Figure 5). At first, the sensor service connects to the simulation bus to reflect on the available entities. After a client registered for a camera component, an update requests allows to change the sensor relative placement, sensor orientation as well as to detach it from the entity of interest again (fixed position sensor). On another request, the sensor returns the endpoint of the video stream considering the selected camera spectrum, an optical, infrared or thermal view. The video stream itself is based on STANAG 4609 which includes metadata regarding the sensor configuration, too.

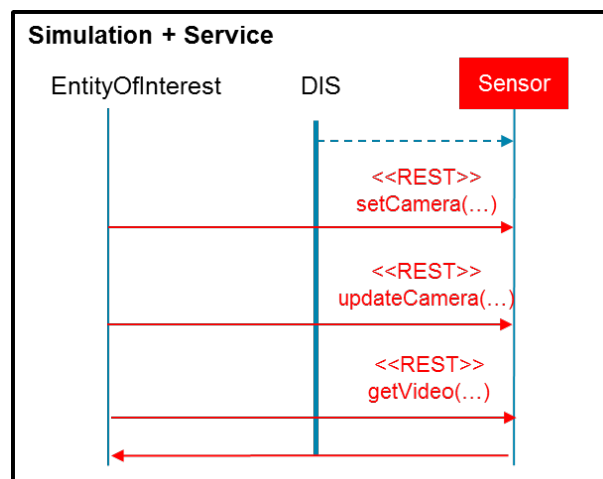


Figure 5: Communication model in context of virtual sensor

3.4 Virtual Cockpit of Eurofighter

The flight training device (FTD) Eurofighter simulation features a cockpit similar to the conventional cockpit in Figure 6. It incorporates three full colour multi-function head-down displays (MHDDs), a wide angle head-up display (HUD) as well as other command and control elements to interact with the Eurofighter. As a separate input device a throttle and centre stick (HOTAS) is attached to the FTD system.

A LITENING targeting pod (LDP) is an advanced precision targeting pod system currently operational with a wide variety of aircraft worldwide, including the Eurofighter. LITENING significantly increases the combat effectiveness of the aircraft during day, night and under-the-weather conditions in the attack of ground and air

targets with a variety of standoff weapons (i.e., laser-guided bombs, conventional bombs and GPS-guided weapons). The targeting pod contains a high-resolution, forward-looking infrared (FLIR) sensor that displays an infrared image of the target to the aircrew.

As a replacement for the missing physical targeting device, the virtual sensor service is used to inject an infrared camera view into the MHDD. The same service interface is used to forward the optical camera view to the HUD representing the (environment) view in front of the cockpit. The camera views are synchronized in regards to position and orientation over the simulation bus which is crucial to a sound user experience.



Figure 6: Illustration of a conventional Eurofighter cockpit

3.5 COP Service

The COP service is a lightweight JavaScript based client side web application. It Uses OpenLayers to display all types of maps using any OGC WMS (Web Map Service – see [8]). The COP may be used as a static scenario editor / visualizer. In addition, the user interface supports the visualization of KML [9] and MSDL [10] files for dynamic military scenarios including APP6 symbology.

For this concept demonstrator, the COP service in Figure 7 receives the ground truth unit positions and tactical symbols through KML which is provided by a REST service hosted by the PAXSEM CGF service.

The COP service is able to remotely control the PAXSEM CGF simulation run. So, the operator is able to start, pause and stop a given scenario. The simulation control hereby is performed through a REST interface of PAXSEM.

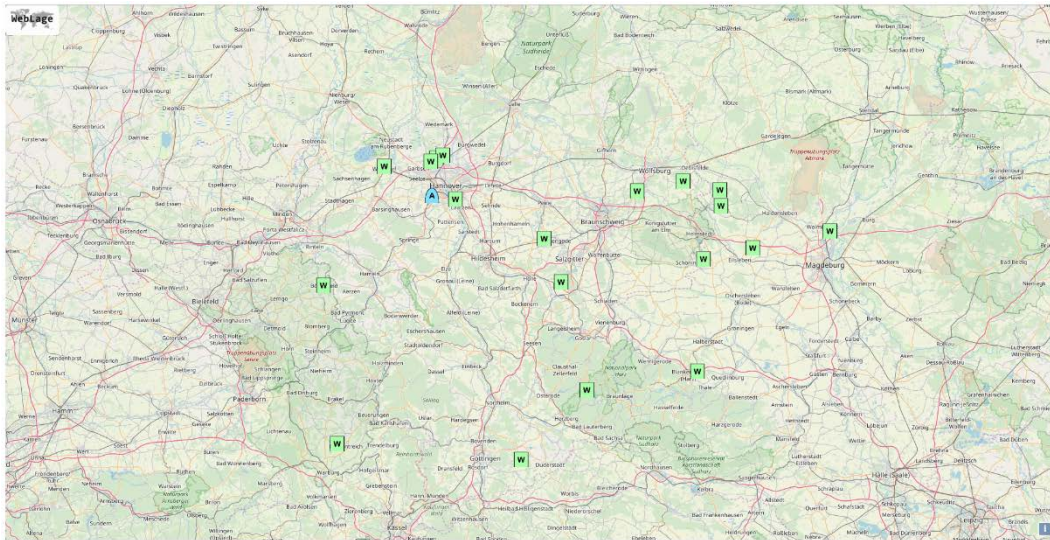


Figure 7: Web application displaying COP

4.0 SENSOR SERVICE IMPLEMENTATION DETAILS

The workflow diagram of the sensor service in Figure 8 shows the inner details that consist of an offline process as well as a runtime process:

The result of the offline process is a generated terrain for the 3D simulation model PAXSEM and an infrared database that includes (surface) temperatures and atmospheric information specific for the former result. In the later runtime process these two results are crucial for applying and using the sensor service.

The individual steps of workflow are described in the next two chapters more in detail.

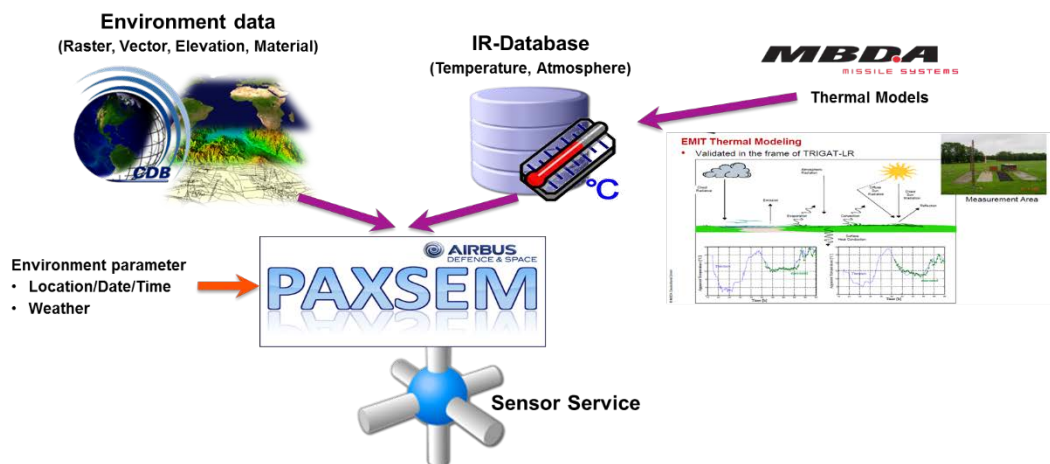


Figure 8: Workflow process of (infrared) sensor service

4.1 Preparation of the sensor service in offline context

In the preparation phase the environment data is examined with regards to the central CDB model which defines a structure for a single, “versionable”, virtual representation of the earth. For the service implementation the main focus is on the CDB layers: imagery, altimetry and material.

On the one hand, the layer data is used to generate an optimised terrain for PAXSEM, due to performance reasons and to thermal considerations. In the latter case, the terrain elements are classified by their material definition (texture-based, pixel-based) so that the infrared model is able to generate sound thermal images, such as emitted radiation from an object and radiation transfer in atmosphere.

On the other hand, the layer data is used as an input for the thermal models which feed the IR-Database with pre-calculated results. This cache mechanism is essential, as it acts as a lookup table for the infrared model.

4.2 Application of the sensor service in runtime context

At first, the sensor service usually loads a scenario (gaming area) on which the scene is playing. This means, the underlying pre-generated terrain is loaded. Moreover, the scenario describes the environment parameters like weather condition, exact date and time and the corresponding location that are valuable information to simulate the infrared view. As a next step, the sensor itself is calibrated with the help of a configuration file which specifies the sensor parameters like field of view, wave length or image filters that are chained together etc.. Last, the thermal information of the infrared database is imported and merged into the runtime context considering the specific scenario situation. That includes the temperatures for the surface, atmospheric radiation paths and relevant scene object material information.

If these preconditions are successfully passed, the sensor service waits for incoming requests to serve the sensor view, either as optical (Figure 9) or as infrared image (Figure 10).



Figure 9: Target view (optical)



Figure 10: Target view (infrared, white hot)

5.0 DEMONSTRATOR SCENARIO

5.1 Scenario Overview

The purpose of this scenario is to demonstrate the feasibility of the MSaaS architecture based on the demonstrator concept as introduced in chapter 2.2. The goal is to use the CGF to provide the simulated environment for all other services. Then, the virtual cockpit is used as a lightweight FTD that interacts with the CGF. Secondly, the controls (of the virtual cockpit) connect to the weapon services as well as the head-up displays reach out to the virtual sensor service to enable a user to interact with the virtual cockpit.

As a quick introduction, the scenario map in Figure 11 shows the initial operational areas and scenario elements which are described more in detail in chapter 5.2.

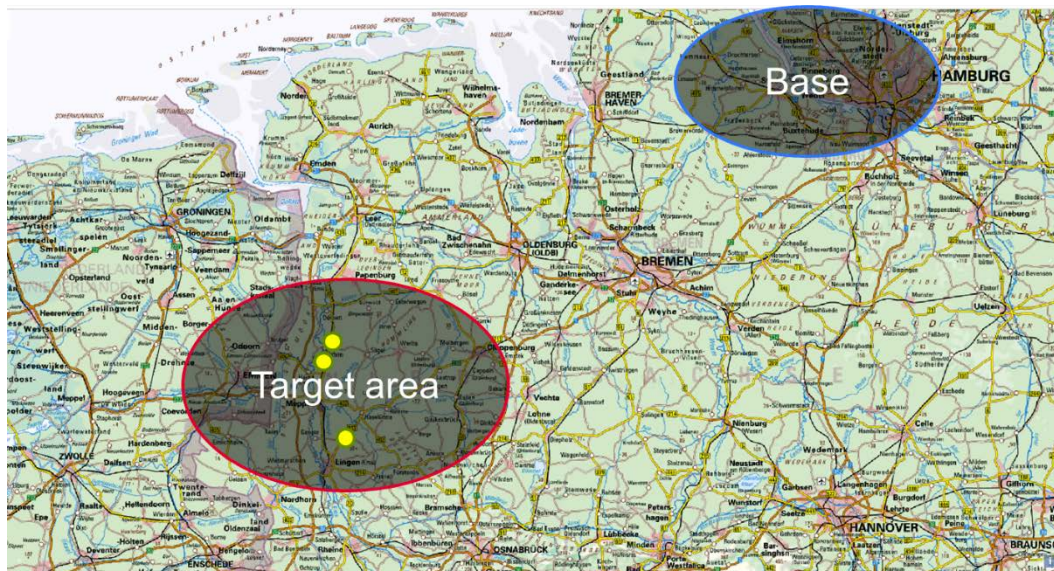


Figure 11: Scenario map and elements

5.2 Scenario Course of Events

Finally, the following technical service workflow is demonstrated:

- All services which are required to initialise with terrain data, execute a request to the central, shared data cloud to setup the virtual environment. The COP service requests this through its OGC WMS interface to a 2D map service.
- The scenario operator starts the CGF service through the COP service, loading a reconnaissance scenario. The CGF service starts simulating a scenario with air- and ground-based simulation entities (e.g., blue air tracks and neutral/red pickups and trucks).
- The CGF service tasks a simulated air track to conduct a reconnaissance mission. The updated picture is displayed in the COP service in parallel.
- The air track arrives at the target area and detects some suspicious vehicles. One of the vehicles is attacking the air track on its mission. The weapon effect and damage state for the air track are calculated by the central WES, if any.
- Based on the current situation, the air track is leaving the target area and returning to home base.
- As a result, the virtual cockpit operator starts from home base to the target area in order to engage the enemy forces. During the movement, the HUD is displaying the optical image that is requested from virtual sensor service as well as the MHDD is displaying the infrared information.
- The virtual cockpit operator targets to the enemy forces and shoots missile which is calculated by the central EWS. Depending on the engagement results, the service sends a munition detonation or not.
- After successful engagement, air track returns to home base and ends mission.

6.0 SUMMARY & OUTLOOK

MSaaS and cloud-based or cloud-native M&S will impact all future simulation environments and acquisition programs. This activity demonstrates that MSaaS and cloud-based simulation is not only an idea existing on slides, but actually works (today!) in operationally relevant environments.

The underlying technology that is used for the MSaaS environment (here: Docker) will be further extended and stabilized, concerning the demonstrator setup, until end of 2019. It's envisaged to verify the advantages of containerisation solutions such as rapid setup and deployment of simulation experiments as well as reusing container services to foster scaling effects.

A central component in the demonstrator environment, the flight training device, currently requires to setup a HLA runtime infrastructure. This means that a HLA/DIS gateway is necessary to forward the data messages within the simulation bus. In the future, the FTD will support the DIS communication protocol which simplifies the setup even more, as no HLA RTI is required anymore.

Finally, to validate the outcome of the proof of concept implementation, it's important to participate in international experiments like VIKING in order to connect to other services and also to offer own services to other possible clients.

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Development of an Air Operation eXtension with the (future) C2SIM Standard

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Keywords: Interoperability, command and control, simulation, C2SIM, air operation

ABSTRACT:

The MSG 145 group is working on the Operationalization of Standardized C2-Simulation

Interoperability, side-by-side with the Simulation Interoperability Standards Organization (SISO) Product Development Group (PDG) which is developing the C2 System to Simulation System Interoperation (C2SIM) standard. The C2SIM standard will improve upon and replace the currently existing combination of Military Scenario Definition Language (MSDL) and Coalition Battle Management Language (C-BML) SISO standards, with a modular approach enabling users of different domains to define their needs in extensions. The main elements of the C2SIM standard are a core logical data model (created as ontology), an extension

mechanism, and several extension ontologies (e.g., Land Operation eXtension). The C2SIM standard also supports the transformation of the exchanges (tasking/reporting messages, initialization of C2 and simulation systems) into Extensible Markup Language (XML) schemata.

This paper describes the work done by a French-German subgroup of the MSG-145 to implement a new C2SIM extension for an Air operation domain. The work includes the operational analysis of an Air operation scenario, the design of the logical model with ontologies, the generation of the XML schemata, and their implementation in the systems. This paper concludes with lessons learned, and contributes to the evaluation of the operationalization and the extension of the C2SIM standard.

1.0 INTRODUCTION

The involvement of modeling and simulation systems (M&S systems) into training and eventually into operations would add value to both, it would increase the realism and complexity of training sessions, and it would offer enhanced tools for mission planning, for decision making, and for after action analysis. A Simulation Interoperability Standards Organization (SISO) Product Development Group (PDG) is developing a standard for Command and Control System to Simulation System Interoperation (C2SIM) [13] in order to support this approach and to make it possible. The SISO efforts, as evoked by [5], have always been supported by NATO activities [7], currently by the NATO MSG-145 “Operationalization of Standardized C2-Simulation Interoperability”. As it has already been proposed in preceding papers [3, 11], this C2SIM standard will replace and improve upon the currently existing Military Scenario Definition Language (MSDL; SISO-STD007-2008) [17, 19] and Coalition Battle Management Language (C-BML; SISO-STD-011-2014) [16] SISO standards. As also has been presented and discussed, the current work in the PDG is specifying a core logical data model ontology, in short a core ontology [2, 11], and a tool to transform the relevant parts of that ontology into an Extensible Markup Language (XML) schema [3]. That schema will serve as a medium for the exchange of messages among systems that constitute C2SIM coalitions. The schema has to support initialization as well as military information exchange during a simulation run, e.g. the exchange of orders to command simulated and real units or the exchange of reports sent by those units.

The paper at hand describes work done by a French-German subgroup of the NATO MSG-145 to implement a C2SIM extension that covers the Air operation domain. The work includes the operational analysis of an Air operation scenario, the design of the ontology extension, the evaluation of a schema generation process when applied to military messages specific for Air operations, and the implementation of the messages within C2 systems and simulation systems. In the following, we will first explain how our work is embedded in the general context and the SISO PDG efforts (section 2). In particular, we will discuss ontologies (subsection 2.1) and their role in the C2SIM context (subsection 2.2). From that, we will discuss automatic schema generation out of ontology representations (subsection 2.3). In a second part (section 3), we will discuss the specifics of military communications in the Air operation domain (subsection 3.1), how these specifics can be represented in an ontology extension (subsection 3.2), and the consequences this has for schema generation (subsection 3.3). The paper continues with the collection of lessons learned from this work (section 4) and concludes with a summary and with the presentation of projected follow-on activities (section 5).

2.0 THE C2SIM CONTEXT

A collection of C2 systems and simulation systems constitutes a C2SIM coalition if the systems can seamlessly interact with each other using the C2SIM standard. For example, a system of two C2 systems and two simulation systems might be used in a training session in which a trainee uses one of the C2 systems to command a simulated force. That force might be simulated on one of the simulation systems. The second C2 system then can be used by the trainer to command opposing simulated forces whose actions are simulated

on the second simulation system. In that scenario, trainee and trainer send orders to their respective forces and expect to get reports back. Therefore, the C2 systems need to interact with the respective simulation systems, and the simulation systems need to interact in order to show both, the trainee and the trainer, pictures of the same situation. Of course, the pictures will differ for both sides. In particular, the trainee will not see the whole ground truth of the opposing forces (this is not a chess game). The work by the SISO PDG and the supporting NATO research group, in general, and the work by the French-German subgroup, in particular, focuses on the interaction between the C2 side and the simulation side. It is about the exchange of military communication. A correct exchange might easily be granted if the participating C2 system(s) and simulation system(s) have been developed by the same maker or at least are systems run by the same nation. However, there are many nations in NATO, and each nation has its own systems. Thus, the challenge is interoperable exchange across multiple diverse systems developed by multiple nations. As it has already been mentioned, such an interoperable exchange had been granted by the C-BML standard (SISO-STD-011-2014) and the interoperable initialization had been granted by the MSDL standard (SISO-STD-007-2008). However, the cooperation of MSDL and C-BML turned out to be difficult. In contrast, the current C2SIM provides an integrated solution. Besides, C2SIM defines an extensible standard. In addition, it had adopted ontology, and more specifically the Web Ontology Language (OWL) [20], as the C2SIM main representation. The latter leads us to the question: what are the benefits of an ontological representation?

2.1 Ontologies and the Web Ontology Language (OWL)

“Ontology”, according to the Encyclopædia Britannica, is “the theory or study of being as such; i.e., of the basic characteristics of all reality.” Rudolf Goclenius the elder coined that philosophical term in the 17th century for what had originally been “metaphysics” in the ancient times [10].

In information science, ontologies are used to represent knowledge. According to the well-known dictum by Tom Gruber, “[a]n ontology is an explicit specification of a conceptualization” [6]. In short, in information science, ontologies are used to unambiguously define the vocabulary of a domain and to express (semantic) relations among the defined terms. Since in information science it is possible to establish ontologies for different domains, the term “ontology” can be used as a plural. This is in contrast to the philosophical “ontology” which is a singular-only noun.

The World Wide Web Consortium (W3C) offers a large palette of techniques to describe and define different forms of ontologies in a standard format. These include Resource Description Framework (RDF), RDF Schemata, and Web Ontology Language (OWL). An OWL ontology consists of a set of axioms which place constraints on sets of individuals (called “classes”) and the types of relationships permitted between them. The data described by an ontology, or an “OWL expression”, is interpreted as a set of “individuals” and a set of “property assertions” which relate these individuals to each other. Furthermore, because the OWL axioms provide semantics and have mathematical “roots” in set theory (with axioms for union, intersection, and complement of classes, i.e. sets of individuals); use of OWL allows systems to infer additional information based on the data explicitly provided. The automated reasoning capabilities of OWL are based on this inference mechanism.

2.2 Ontologies in the C2SIM Context

The idea of using ontology to support C2SIM and the interoperability among participating systems dates back at least to 2005, cf. [1], “but was postponed for the benefit of first developing an exchange language based on formal syntax (CBML)” [3]. After the C-BML standard had passed, the idea was revived in order to examine its potential, cf. [2]. In principle, there are two domains from which knowledge, when formally represented in an ontology, may provide benefits in the C2SIM context. These are military operations as well as military communication. First, knowledge about military operations accessible by a C2 system can improve for example automated decision support. Therefore, it also can improve C2SIM applications like

staff training. For example, if logistic states for the units of one's own forces would be known and exploitable for a C2, the system could warn a commander of possible overreaches when tasking forces. Second, there is the domain of military communication. Military communication follows rules and formats recorded in specific regulations and instructions. These rules and regulations can be represented within a domain ontology covering military communication; e.g., for every kind of message it can be represented by a Boolean value whether the receipt of the message has to be acknowledged. The benefit would be an increase of realism in C2SIM; e.g., simulation systems could generate acknowledgements if a simulated unit receives a message from the user of the connected C2 system of a kind that is marked to be answered by an acknowledgement. The latter idea has already been proposed in Singapogu et al. [15]. Therefore, the PDG's core ontology provides the class "Message" with some subclasses where knowledge about military communication can be stored. In general, it must be acknowledged that we have barely scratched the surface on the use of ontologies for knowledge representation, automated reasoning, information linking, and information query. But, in C2SIM, we opened the door in the secure knowledge that there are numerous open source and commercial tools available that will enable rapid adoption and exploitation of ontologies in the military domain.

2.3 From Ontologies to Schemata

Ontologies represent knowledge. Schemata allow the exchange of messages. From a linguistic point of view, good ontologies have to represent the necessary knowledge correctly. They constitute semantics. In contrast, good schemata transmit their messages in a correct form. They constitute syntax. Nevertheless, the receiver of a message should understand the message's meaning as intended by the sender. Therefore, schemata need to refer back to ontologies. In C2SIM, we consider this insight: we generate the schemata automatically out of the ontology. Blais et al. presented the respective tool. Their paper [3] provides details about schema generation using the tool. With the paper at hand, we will focus on the details and the specifics that hold for the Air operation domain and its specific military operations. However, before we will unfurl this topic in the following section, we would like to stress that automatic schema generation out of an ontology does not mean that everything that is represented in the ontology will be reflected in the schemata adjusted for specific applications. The schemata only need to enable initialization and message exchange. Thus, only those ontological representations that are needed for these processes need to appear in the schemata. All other ontological representations, may they be mandatory for other ontological processes or not, can be omitted.

3.0 AIR OPERATIONS IN C2SIM

Most C2SIM demonstrations of the past focused on land operations, with sometimes enhancements and complements to deal with maritime [14] and/or air operation [4, 8, 18]. Beyond the mentioned contributions, modelling air operations in C2SIM needs further efforts. In order to cover air operations' aspects, we first have to consider the specifics of air operations in general and the specifics of military communication in air operations in particular (subsection 3.1). Having identified those specifics, we have to represent them in an ontology extension for air operations (subsection 3.2). Last but not least, we have to take a look at the automated schema generation (subsection 3.3). It needs some add-ons, so that the resulting schemata allow air operations' specific communications.

3.1 The Specifics of Air Operations

Air-mobile forces excel in tactical mobility and speed. They are characterized by their dynamics. Therefore, communication with air-mobile forces differs from communication on the army side. For example, the army command can track ground forces if these forces send position reports providing their current positions, e.g., in the form of coordinates, periodically. In contrast, due to the already mentioned high dynamics, aircraft are tracked by automated position updates, generated e.g. by an airborne radar picket system, like an AWACS.

The resulting tracks are branded with track numbers. These numbers then allow referring to an air-mobile force or even to a single aircraft in further communication. The communication in air operations, i.e. the exchange of messages including orders, requests, and reports, uses data link standards such as the NATO standards TDL (Tactical Data Link) 11 and TDL 16, also called “Link 11” and “Link 16”, respectively. Link 11 is described in STANAG 5511 and the US MIL-STD-6011 and will be replaced by Link 22. Link 16 is described in STANAG 5516 and the US MIL-STD 6016. In our approach for air operations, the focus is on having generic messages for TDL networks in general, as suggested in Svensson et al. [18].

The scenario is based on a fictional operation executed by the Future Combat Air System, to destroy hostile air defense (Destroy Enemy Air Defense / DEAD scenario). For such operations, the fighters, the drones swarms, and the AWACS are all connected through a TDL network (Link 16, or maybe a new one in the future), and they exchange messages for situation awareness (tracks, own positions, targets) and for command and control. Our experimentation involves the simulation DirectCGF (DIGINEXT) and the C2 surrogate C2LG (FKIE). DirectCGF simulates all the entities on the battlefield. C2LG plays the command and control function of the AWACS on a subset of the entities. All other AWACS tasks, e.g. surveillance and the command and control of other entities, are simulated by DirectCGF.

In order to create realism in C2SIM also in the air operation context, TDL messages have to complement the standard message portfolio as used in C2SIM. In addition, the secure data network that allows the exchange of TDL messages in air operations needs to be considered in the simulation. Consequently, we represented the TDL messages as well as the network, ontologically, as explained in the following subsection.

3.2 Air Operations and Air Operation Communication Represented Ontologically

In order to represent air operations, ontologically, we built a respective ontology extension to the ontology that already has merged the C2SIM core with its standard military extension (SMX). The core ontology provides a taxonomy with classes subsumed under the upper classes “C2SIMContent”, “InitializationConcept”, and “MessageConcept”. These split up into various subclasses that inherit properties from their superclasses as restrictive definitions of them.

In the following, we explain how we have built the air operation extension by discussing the construction of three example classes all of which are crucial for air operations. On the platform side, no class enhancements are needed to add to our air operation extension. The various platform types will be defined by new instances of the C2SIM classes “DISEntityType” and “APP6-SIDC” in the scenario initialization data.

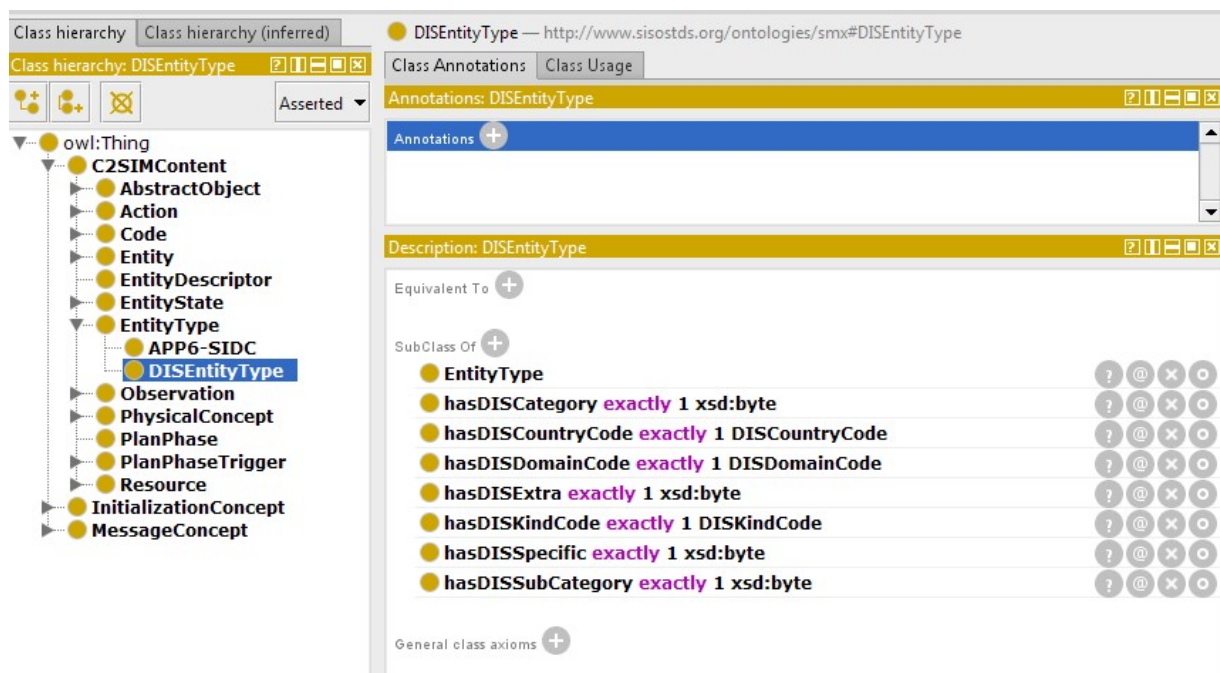


FIGURE 1: Snapshot of the part of the ontology's taxonomy that is about entity types; the snapshots are taken from the implementation of the ontology in Protégé [9]

The C2SIM core ontology already has the class “CommunicationNetwork”. It can be used to represent a Tactical Data Link network in the scenario. During initialization, an instance of that class is generated by applying what is represented in the class “TDLNetworkParticipantDefinition”, subclass of “InitializationConcept”, cf. figure 2. “TDLNetworkParticipantDefinition” has the property “hasCommunicationNetworkUUID” to refer to a network instance and the properties “hasSubjectEntity” and “hasTDLTrackNumber” to assign an entity together with its track number to the network.

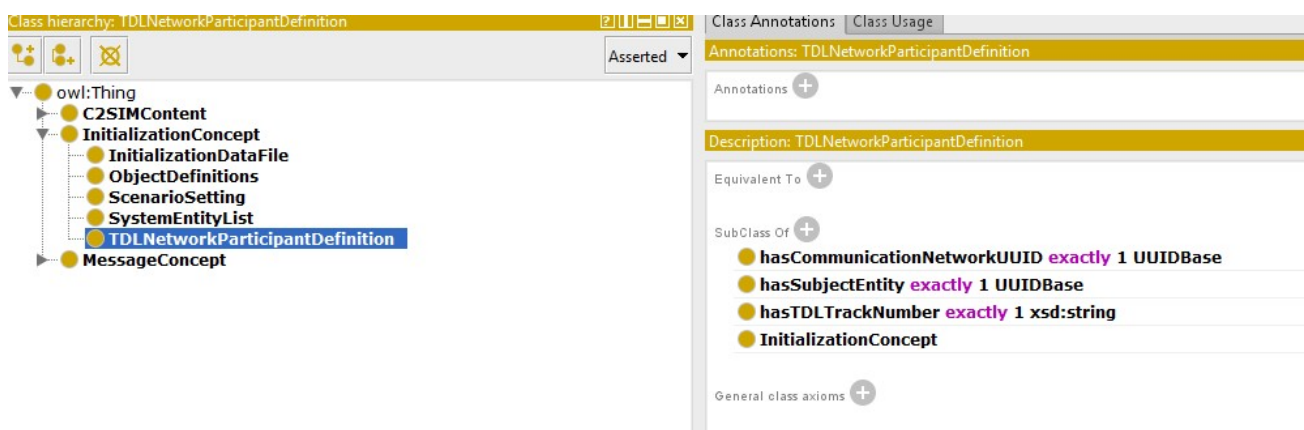


FIGURE 2: Snapshot of the part of the ontology's taxonomy that represents knowledge to be applied during initialization

Since C2SIM is an approach to substitute C-BML (besides MSDL), messaging remains crucial. The C2SIM core ontology provides a general structure of messages that allows adding subclasses for specific messages for different domains.

Specific messages come with restrictions, e.g. how orders and reports should be structured and which elements or pieces of information they should include. In the French-German air operation extension, we paid attention to abide by the structure as provided by the core. As TDL includes specific information and extend the domain formerly covered by C-BML, we introduced the class “TDLHeader” as well as specific classes under “ReportContent”, “RequestBody”, and “OrderBody”

(in the core ontology, as published by the PDG, “ReportBody” refers to “ReportContent”). In the following, we will illustrate our approach by examples. Our first example is the TDL PPLI. Its representation in the ontology is given in figure 3.

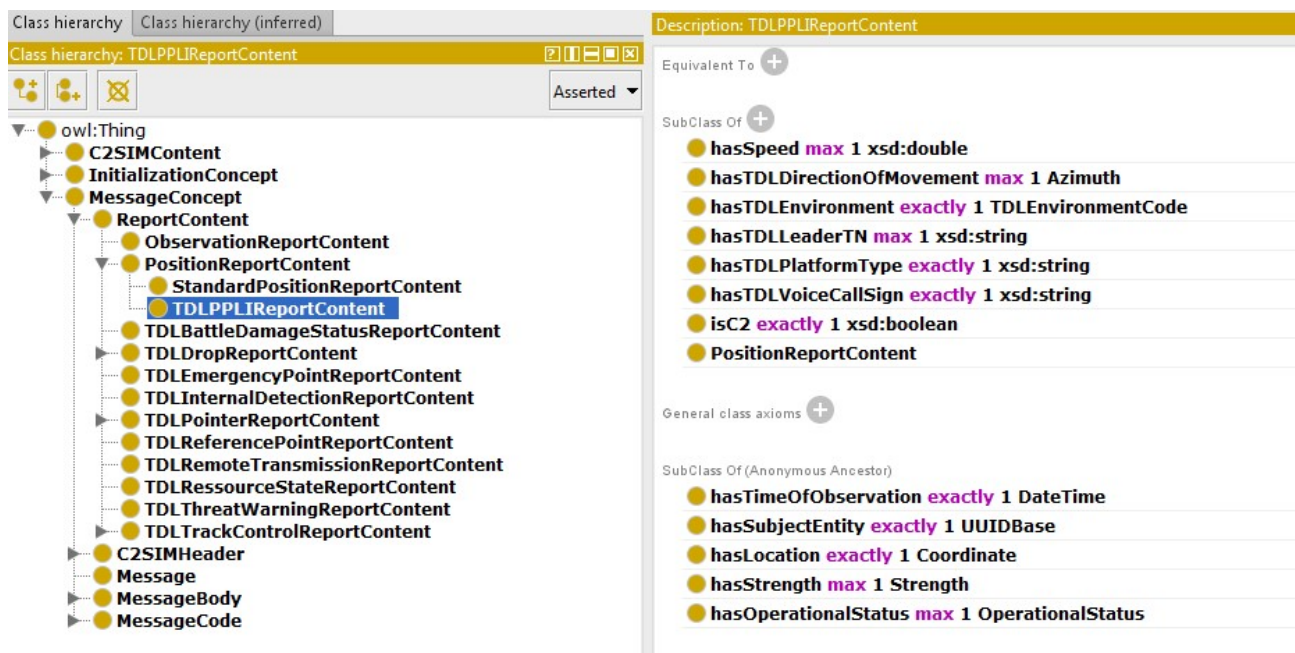


FIGURE 3: Snapshot of the class “TDLPPLIReportContent”

As can be seen on the left side of figure 3, TDL PPLI is represented as a position report. PPLI is the abbreviation for “precise participant location and identification” meaning that the sender reports about its own position, with additional information when necessary. The class for the body and thus for the content of a TDL PPLI (“TDLPPLIReportContent”) is a subclass of “PositionReportContent” because it needs more property restrictions than “PositionReportContent” from the core to be defined. However, this expansion leads then to an artificial construction of “StandardPositionReportContent” as a complement to “TDLPPLIReportContent” as all classes need at least one sister class with at least one additional property to fulfill ontology principles. “TDLPPLIReportContent” (just as its sister class) inherits all properties of “PositionReportContent”, including mandatory statements about the subject whose position is reported, of the responding location and of the respective point in time (figure 2, right side, lower part). “TDLPPLIReportContent” has some properties that are specific and not inherited from “PositionReportContent”. These properties derive from the TDL PPLI’s fields and are named respectively. For example, the property that derives from the TDL PPLI’s field “Environment” is named “hasTDLEnvironment”. In general, following conventional ontological naming, a property’s name starts

with “has” or “is”. In order to indicate that the property has been added for/by this extension, “TDL” is included in the name followed by the respective field’s name. If there was already a property as part of the C2SIM core ontology (or existing extensions) that corresponds to the field, that property would have been used. In these cases, no “TDL” tag would be in the name. The properties that derive from the TDL PPLI include the subject’s speed (“hasSpeed”), its direction of movement (“hasTDLDirectionOfMovement”), and the track number of its leader (“hasTDLLeaderTN”) whereas its own track number is provided in the report’s header. Some more properties are in the body. They can be used to provide more information about the sender, but they can be seen as superfluous since the subject’s id and track number are given in the report’s header. Nevertheless, the properties are included so that all fields of the TDL are covered. The superfluous properties are “isC2”, “hasTDLPlatformType”, and “hasTDLVoiceCallSignal”. Another property is the already mentioned

“hasTDLEnvironment”. It always bears the value “AIR” in our context.

As a second TDL message example, we would like to discuss the “Mission Assignment” message of the TDL domain. In the C2SIM context, it’s semantically the same thing as an order message, sent from a commander to the subordinated aircraft, with a single task containing the details of the “air mission”. So, we decided to create the class “TDLMissionTask”, as a subclass of the C2SIM “Task”, and use the C2SIM order message.

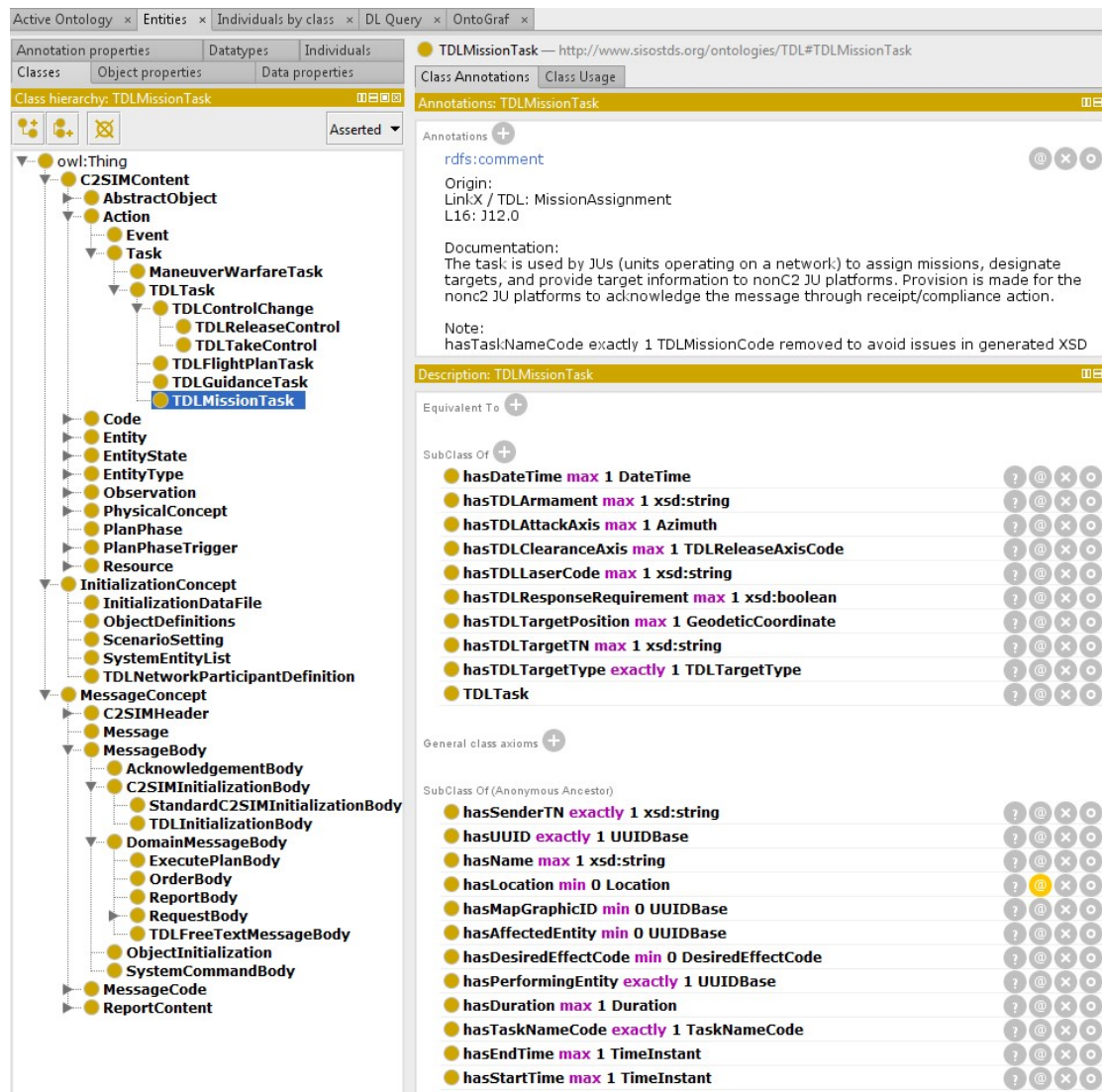


FIGURE 4: Snapshot of the class “TDLMissionTask”

As depicted in Figure 4, “TDLMissionTask” is not directly a subclass of “Task”. We’ve added also the “TDLTask” class, in order to have a common root for all kind of tasks exchanged over TDL networks. The other TDL tasks are used for guidance commands (take a new direction, take a new altitude, speed, etc.), or to order to follow a flight plan (points with dates/times). “TDLMissionTask” inherits all the properties of the C2SIM “Task” class, which includes a task UUID (property “hasUUID”), a reference to the taskee (property “hasPerformingEntity”), and the mission verb (property “hasTaskNameCode”). “TDLMissionTask” is defined with new property restrictions: an instance of “TDLMissionTask” is an instance having one property “hasTDLTargetType” (which should define the type of the target), and having maximum one property “hasTDLTargetTN” (which should define the Track Number of the target), and having maximum one property “hasAttackAxis” (which should define the direction of the aircraft before the aircraft launches its missiles), and so on. “TDLMissionTask” represents all TDL missions with verbs like e.g. “attack”, “escort” or “cover”. As mentioned before, “TDLMissionTask” inherits the property “hasTaskNameCode” and the corresponding range from its superclass “Task”. However, the values that “TDLMissionTask” permits for TDL tasks constitute only a subset of all the values of

“TaskNameCode”. We took into consideration restricting the range of “hasTaskNameCode” for “TDLTask” to those codes that refer to a TDL task. However, this would lead to a double occupancy of that property resulting from inheritance, meaning “TDLMissionCode” would be defined by having a TaskNameCode exactly 1 TaskNameCode and exactly 1 TDLTaskCode. And this assertion would be wrong. Therefore, we did not restrict this property further.

3.4 Exchanging TDL Messages: From Ontology to Message

```
<?xml version="1.0" encoding="UTF-8"?>
<Message xmlns="http://www.sisostds.org/schemas/C2SIM/1.1" xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
xsi:schemaLocation="http://www.sisostds.org/schemas/C2SIM/1.1 file:///C:/C2SIM/Comelec/Airbus/C2SIM_SMX_LOX_TDL.xsd">
  <C2SIMHeader>
    <StandardC2SIMHeader>
      <CommunicativeActTypeCode>Inform</CommunicativeActTypeCode>
      <MessageID>cd1d895f-ea3e-4858-906d-6abc93907a5d</MessageID>
      <Protocol>C2SIM</Protocol>
      <ProtocolVersion>1.1</ProtocolVersion>
      <SendingTime>2019-07-30T13:36:30:Z</SendingTime>
      <FromSendingSystem>C2LG</FromSendingSystem>
      <ToReceivingSystem>DirectCGF</ToReceivingSystem>
      <ConversationID>d10f9a43-e4ea-4edc-9ede-ebde7d5e1eb2</ConversationID>
    </StandardC2SIMHeader>
  </C2SIMHeader>
  <MessageBody>
    <DomainMessageBody>
      <OrderBody>
        <FromSender>00000000-0001-0001-1000-000000000000</FromSender>
        <ToReceiver>00000000-0000-0001-2000-000000000000</ToReceiver>
        <Task>
          <TDLTask>
            <TDLMissionTask>
              <TaskNameCode>ATTACK</TaskNameCode>
              <PerformingEntity>00000000-0000-0001-2000-000000000000</PerformingEntity>
              <UUID>cd1d895f-ea3e-4858-906d-6abc93907a5e</UUID>
              <Name>TDLMissionTask_1</Name>
              <TDLMissionType>ATTACK</TDLMissionType>
              <TDLTargetType>AIR_DEFENSES</TDLTargetType>
              <TDLAttackAxis>
                <Angle>90</Angle>
              </TDLAttackAxis>
              <TDLClearanceAxis>LEFT</TDLClearanceAxis>
              <TDLTargetPosition>
                <Latitude>50.397138</Latitude>
                <Longitude>9.862633</Longitude>
              </TDLTargetPosition>
              <TDLArmament>missiles</TDLArmament>
              <TDLTargetTN>501</TDLTargetTN>
            </TDLMissionTask>
          </TDLTask>
        </Task>
        <IssuedTime>
          <DateTime>
            <IsoDateTime>2019-07-30T13:36:30:Z</IsoDateTime>
          </DateTime>
        </IssuedTime>
        <OrderID>cd1d895f-ea3e-4858-906d-6abc93907a5f</OrderID>
      </OrderBody>
    </DomainMessageBody>
  </MessageBody>
</Message>
```

LISTING 1: TDL mission order as completed XML structure conforming to the generated schema

Blais et al. [3] describe how schemata are generated from ontological representations. This approach starts with merging the C2SIM core with all required extensions. The schema is then transformed out of the merged ontology. In our case, this process has been applied to the C2SIM core ontology enhanced by the air

operation extension. The result is an extensive schema that covers all kinds of messages, those for initialization as well as those for the different kinds of military communication. Since the ontology has the air operation extension incorporated, this includes TDL messages. In order to exchange information among the systems of a C2SIM coalition, the respective part of the general schema is filled in.

Listing 1 shows an example TDL mission order. In order to express it, the ontological representation of such an order / a task has been processed as described in [3]. During that process, the prefixes “has” and “is” that are used for properties in the ontology are clipped so that for example the ontological property “hasPerformingEntity” is transformed into the tag

“PerformingEntity”. The resulting schema then has been completed with dummy entries.

The listing of the TDL mission order assigns the UUID “00000001-0000-0001-2000-000000000000” to the order, the verb “ATTACK” to the mission, the aircraft UUID “00000000-0000-0001-2000-000000000000” that will perform the mission, the track number “501” of the target, the type “AIR_DEFENSES” of the target, etc.

4.0 LESSONS LEARNED

In this section, we point to some of the lessons we have learned when we developed the Air Operation extension for the C2SIM standard. The lessons refer to different steps from the process of designing an ontology extension that is to abide by the C2SIM structure and, in addition, refer to issues that evolved when we tuned the ontology extension so that the transformation process results in a valid schema.

- *Enumerations (how to deal with them)*

If an ontology, such as the C2SIM core ontology, defines classes being subclasses of others, an extension not always adds details like additional properties but also may limit existing properties in range. An example for that is “TaskNameCode” inherited from class “Task” to class “TDLTask”. “TaskNameCode” among others allows the value “withdraw” which, however, does not name a TDL task (cf. section 3). Most commonly, the value of a TDL field is one element out of a fixed set of an enumeration. The enumeration is provided by the TDL experts to support various data links such as Link 16 [18]. The elements can even correlate with classes from different fields in the core. To keep the TDL elements together building a single enumeration type, they are “subordinated” to one single class. We decided to model the enumeration values as individuals. This allows pointing directly to these specific enumeration values (the individuals) from different perspectives and classes. It is also possible to declare two individuals as being equivalent.

- *Property ranges, restrictions and leaf classes*

If C2SIM users add subclasses to the core superclasses, it is because they need to add more properties or to specify existing properties of a class.

Creating a new subclass with new properties to specify a class requires building a new sister class as well. This is the case in the “PPLIReportContent” that needs a new sister class “StandardPositionReportContent”. If we would have added only “TDLPPIRReportContent” without this additional class “StandardPositionReportContent”, only “TDLPPIRReportContent” could be used in the schema, meaning that it would have been impossible to exchange only a “PositionReportContent” element.

If a class inherits a property from its superclass, it might happen that the range for that property is restricted more closely in comparison to the property’s range as defined for the superclass. For example, the class “Task” has the property

“hasTaskNameCode”. Its range is an enumeration of the codes for all assumed tasks. The class “Task” has

the class “TDLTask” as subclass. “TDLTask” inherits “hasTaskNameCode” but only some of the codes that constitute the enumeration list for “hasTaskNameCode” are codes for TDL tasks. Therefore, we would like to restrict the range of “hasTaskNameCode” for “TDLTask” to those codes that refer to a TDL task. However, if we do this, the schema generated out of the ontology will show two lines for “hasTaskNameCode” (first issue), one for the original enumeration and one for the restricted enumeration, and both having the same range (second issue).

The second issue arises because the range of the property restriction is not taken into account in the schema generation process. Only the range of the property definition is used. We get around this issue by creating several properties with different range definition, and use the appropriate property for the property restriction.

The first issue is a general problem, at least in the C2SIM context. We think that the schema needs not necessarily to be restricted as narrow as possible in the general case, at least not for message exchange. However, for future reasoning, restricting the ranges as narrow as possible seems to be expedient. Currently, in order to achieve a working prototype, we have not added restricted restrictions to respective subclasses such as “TDLTask”. Instead, we trust the users to generate meaningful messages, e.g. only to use codes for TDL tasks if the task is a TDL task.

□ XSD errors

The last issue identified with the C2SIM schema generation process is that the generated schema (XSD) is not always compliant with the W3C standard. Sometimes, there are some errors in the generated schema that can be seen when the schema is loaded in an editor checking the XSD syntax (Eclipse editor, XML Spy). These errors are all about a name (example “TDLEnvironmentCode”) that cannot be resolved to a(n) ‘element declaration’ component within the XSD file. Currently, the solution is to add manually some instructions in the generated schema, such as:

```
<xs:schema [...]>
  <xs:element name="TDLEnvironmentCode" type="TDLEnvironmentCodeType"/>
  [...]
</xs:schema>
```

The reasons for these errors have not been evaluated, yet. We assume that this could be due to some OWL definitions in the modeling of the Air Operation extension that have not been implemented yet in the generation process. There is work in progress on this issue at the SISO C2SIM PDG, too.

5.0 FUTURE WORK

This paper discusses the process of developing an air operation ontology extension to the C2SIM core ontology so that the transformation of the entire ontology (core plus extension) results in a valid schema. As the work is still in progress, updated versions may be forthcoming. Even more, not all ontology capabilities have been exploited, yet. In particular, the PDG is planning to use reasoning capabilities of OWL and increase the realism of C2SIM. This also may entail further adjustments to the ontology.

In the paper, we argued that ontologies increase the realism of C2SIM. Two domains have been identified from which knowledge can be represented ontologically for such a purpose. The first domain is military operations. In order to exploit knowledge about military operations, reasoning is needed. We did not explore the chances of such an approach so far. In the current state, operational realism is granted by the simulation systems that are incorporated in a coalition of a C2SIM demonstration. But because we couldn’t use some of the OWL axioms related to the set theory (union, intersection, complement of) and some design constructs (subclass of multiple classes, equivalences, etc.) we cannot assess the reasoning capabilities that the current C2SIM standard will foster.

The second domain is military communication. With respect to this domain, the realism of C2SIM can be increased easily by implementing the ideas proposed by Singapogu et al. [15]. This can be done by adding two Boolean properties to the class “Message” coined “needsAcknowledgement” and “needsAnswer”. These properties come with the default value “false”. For the subclass “Order” the property “needsAcknowledgement” is set to “true” and for the class “Request” both properties are set to “true”. Then procedures can be incorporated in the participating simulation systems’ procedures by which they react to the reception of a message so that they generate an acknowledgement whenever they receive a message that shows the value “true” for “needsAcknowledgement”. In addition, they will generate an appropriate committing answer whenever they receive a message that shows the value “true” for “needsAnswer”. As a result, simulated forces would react on receiving orders and requests like real forces do. But, this enhancement is not related to the use of the ontology and

OWL; it is related to the definition of a “new” property in the model. For example, this particular feature/property (needsAcknowledgement) already existed in CBML, with the XSD attribute “AcknowledgementRequested” in a CBML order.

Furthermore, and the SISO C2SIM PDG is aware of that, because some of the object properties have been replaced by data properties (with the UUID of the related object), most of the OWL reasoning features (inference of additional information based on the data provided in an “OWL expression”) might be unusable.

6.0 CONCLUSION

The paper at hand describes the first steps of the development of an Air Operation extension for C2SIM. Guided by a scenario of air operations, an extension of the C2SIM ontology had been fleshed out. The transformation tool provided by SISO’s C2SIM PDG (cf. [3]) had been applied to the result of the ontological work to generate a schema. The resulting schema is supposed to be valid for initialization and message exchange during C2SIM demonstrations that include air operations. We recognize that the current transformation tool is preliminary and is expected to be refined and further developed as C2SIM early-adopters work with the emerging standard and apply lessons learned. In this vein, we identified some suggested improvements in this paper from our investigation into an Air Operation extension. We also have noticed that close cooperation is mandatory among different specialists who are knowledgeable in many domains (OWL, XSD, C2SIM XSD generation, and TDL for our Air Operation scenario). But we also recognize that the C2SIM ontology extension design process is preliminary, and is expected to be refined and further developed, which could facilitate the C2SIM future-adopters work.

When the paper had been finished, the validity of the generated schema had been evaluated in test runs but when the paper is due for presentation, a French German demonstration will have revealed additional pros and cons.

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A New Simulation Infrastructure Supporting the Next Generation of Simulation-Based Testing and Training Applications

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ABSTRACT

The next generation of simulation systems contains new requirements for simulation infrastructures significantly different from current solutions. Current simulation interoperability standards, such as IEEE 1278 Distributed Interactive Simulation (DIS) and IEEE 1516 High Level Architecture (HLA), are updated on a regular basis by standardisation bodies. Nonetheless, their conceptual frameworks and technical structures are rooted in the last decades' technology and often reach their capability limits when applied to support the most recent system engineering challenges. NATO continues to support and apply these standards, despite them being no longer sufficient to support training, education, and testing of next generation defence systems. We present concepts needed to implement a novel simulation infrastructure, centred around an Information Exchange Services Matrix (IESM) and accompanied by supporting services. This allows the application of new technologies and accommodates the evolution of these technologies in support of composable solutions that provide both "fair fight" training and analysis. These general concepts are applicable to the development of a Joint Simulation Environment (JSE) for the next generation of simulation systems. This paper describes the concepts behind the IESM and their supporting services.

1.0 INTRODUCTION

The concept of modelling and simulation (M&S) has been successfully applied in the context of developing new solutions, testing related components and systems, and training future users. To support the reusability of existing solutions for such applications, several interoperability standards were developed and successfully applied. Mainly driven by the defence simulation community, the IEEE 1278 Standard family defining the Distributed Interactive Simulation (DIS) concepts and processes and the IEEE 1516 Standard family defining the High-Level Architecture (HLA) are among the most notable solutions; the latter is even captured in the military standard STANAG 4603. The NATO M&S community relies heavily on standards and agreements, as national contributions should be easily integrated into a multinational solution. To test conformity with standards, NATO only recently provided a new HLA certification process [1]. Overall, the HLA standard has been a success for coalition interoperability improvements, with standards being continuously improved and re-evaluated by users and the standardisation bodies.

The DIS concept originates from SIMNET [2], which was developed in the late eighties. The ideas and concepts underpinning the HLA also date back to the late eighties and early nineties [3], although some newer concepts have been integrated into the latest version, such as better support for web-based—and recently even cloud-based—solutions, together with greater flexibility regarding the information exchange specifications.

Since its introduction, the HLA has been successfully applied in many domains outside of the military, such as in medical environments, transportation, and other domains, such as those discussed in [4]. However,

recent systems engineering challenges—such as development of systems to become part of the Internet-of-Things (IoT) [5], initiatives to support the Industry 4.0 efforts, developing and testing of cyber-physical systems (CPS) [6], or next generation defence systems [7]—often reach the limits of the principles and concepts of distributed simulation. Common challenges observed in these new systems engineering domains are as follows:

- *Significant increase in data utilised by the systems:* IoT and Industry 4.0 systems are networked systems by design, providing the foundation for smart houses, smart cities, smart production facilities, for example. As such, their information exchange requirements are far greater than those of traditional solutions. Similarly, the next generation of defence systems are not only simple effectors on the battlefield, but also provide, disseminate, and utilise information for the distributed battle management process. Likewise, cyber-physical systems are data-intensive as they provide decentralised decision and management structures. Current simulation interoperability standards were not designed for the increase in data required by these systems.
- *Multi-modality of the systems:* Traditional systems usually receive their input via a small set of well-defined interfaces, such as one or two well-defined sensors onboard the system. Current systems, such as CPS, have a multitude of sensors and use a high variety of modalities to communicate with humans, or exchange information with other systems. The same information must be communicated via a large variety of channels, each with its own information exchange formatting requirements. Current simulation interoperability standards focus on one information exchange medium supporting a common structure (such as the protocol data units of DIS or the objects defined in the federation object model of HLA). Multi-modality has not been sufficiently considered.

In addition to these changes in the systems themselves, the nature of operations in which they are applied have also become more complex. Since the current simulation interoperability standards were introduced more than a decade ago, systems engineering has developed new methods and tools to cope with system of systems challenges, emergence in complex environments, and has recently started to study complex systems engineering more intensively, as discussed in more detail in [8].

Although the simulation community has expressed considerable interest in leveraging distributed systems and infrastructures—such as cloud-based services in support of planning, conducting and evaluating complex operations in complex environments (as documented in [9]), and including more extensive use of IoT or Industry 4.0 related concepts—these trends have not yet become part of new standardised simulation infrastructure recommendations. It is suggested that every solution that does not address these new complexity issues will fall short of providing adequate support to its user—including industry, government, and military.

In summary, the evolution of systems' technology as well as the way it is utilised has led to an unforeseeable increase in data exchange requirements, multi-modality, and an increase in distributed operations in more complex environments. In the defence community, additional requirements contribute to the growing number of challenges, such as the need for multi-domain operations across service borders and—in the context of NATO—across national forces as well. A new simulation infrastructure is required that will address these challenges and provide actionable solutions. This new simulation infrastructure will need to take advantage of the same technology advancements that provide interoperability and composability. This will pave the way to incorporate newer M&S technologies and continue to reuse legacy solutions in a new context. At the same time, these new developments in systems' technology not necessarily render existing solutions obsolete. Previously successful concepts that successfully provided solutions for simulation infrastructure challenges need to be integrated and utilised, such as time management services. Therefore, the new infrastructure shall allow the reuse of calibrated existing solutions side by side with the integration of technically improved solutions.

2.0 SIMULATION INTEROPERABILITY SERVICES

It goes beyond the scope of this paper to address all relevant contributions of past and current approaches to provide a standardised set of services and processes to support simulation interoperability. The interested reader is directed to [10] for additional information and references to the details of IEEE 1278 and IEEE 1516, as well as the Aggregate Level Simulation Protocol (ALSP), the Test- and Training Enabling Architecture (TENA), the Extensible M&S Framework (XMSF), or the use of the Semantic Web.

2.1 Tenets for the Simulation Infrastructure

The NATO M&S Group Study MSG-136 (2014-2017) documents the recent technical development in cloud computing technology and service-oriented architecture. This study shows how these developments and architecture offer opportunities to utilise M&S capabilities more effectively to satisfy NATO critical needs [11]. This is of interest for new infrastructure solutions; particularly how they should not become a ‘monolithic bottleneck’ at the centre of otherwise scalable and composable service solutions. Instead, new solutions should expose key characteristics, as presented in Figure 1.

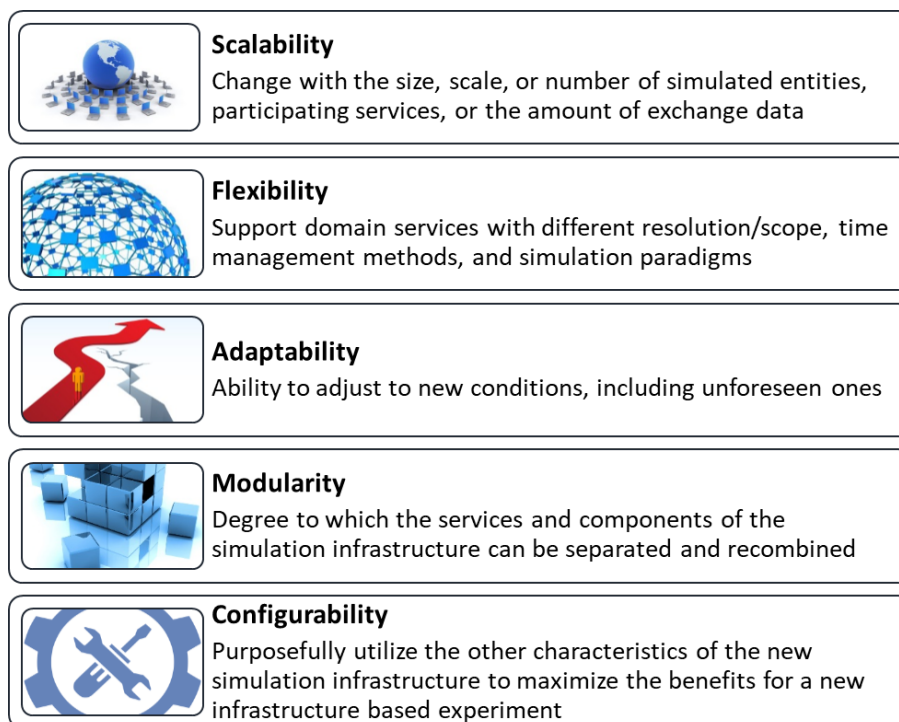


Figure 1: Architecture Characteristics for the Future Simulation Infrastructure

The envisioned concepts should therefore be a set of composable services fulfil the requirements for scalable, flexible, adaptable, modular, and configurable solutions. The infrastructure must ensure that

1. All information needed by the simulation services is provided
2. Only the information needed will be provided
3. The information is provided in a secure and timely manner

Furthermore, a short analysis of current approaches shows conceptual ideas that should be reused to support and leverage recently developed technologies. Our proposed approach to implement the concepts described

in this paper takes advantage of current approaches within the new infrastructure, further evolving them, adapting them, or replacing them with new methods using most recent research insights in both the conceptual and technical domains. Our analysis led us to the conclusion that the services provided by the Runtime Infrastructure (RTI) of the HLA are particularly helpful in guiding conceptual development. The RTI (standardised within the IEEE 1516) provides functions in support of six service categories, depicted in Figure 2.

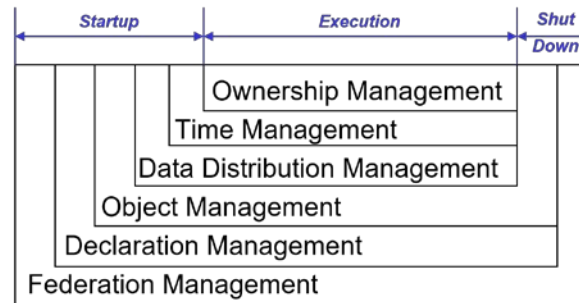


Figure 2: Services provided by the HLA Runtime Infrastructure

- Federation Management determines the federation. Federates join and leave the federation using the functions defined in this group.
- Declaration Management identifies which federate can publish and/or subscribe to which information exchange elements. This defines the type of information that can be shared.
- Object Management manages the instances of shareable objects that are shared in the federation. Sending, receiving, and updating belong in this group.
- Data Distribution Management ensures the efficiency of information exchange. Adding additional filters ensures that only data of interest are broadcast.
- Time Management synchronises the execution of the participation federates.
- Ownership Management enables the transfer of responsibility for instances or attributes between federates.

The RTI introduced innovative concepts to the community. While other interoperability solutions—such as DIS, ALSP, and TENA—all use standardised information exchange objects, the RTI utilises the Object Model Template to allow the declaration and sharing of every piece of information, as agreed between the participating federates. This allows the use of the same infrastructure for very different application domains beyond defence applications. The service groups provided the functionality to utilise this information exchange; however, the price for this flexibility was the need to agree on the semantics of the exchanged objects in additional administrative processes.

2.2 The Information Exchange Services Matrix

When the US Air Force decided to build the Joint Simulation Environment (JSE) as their next generation enterprise training and test capability, the engineers faced the same challenges described in the previous section: how to provide a simulation infrastructure that is fast, secure, and ready for data-intensive multi-modality systems? In partnership with the US Air Force, MITRE is developing a new simulation infrastructure enabling experimentation, rapid prototyping, and concept exploration capability to support testing, training, and acquisition decisions. Conceptual studies have resulted in the recommendation to build an Information Exchange Services Matrix (IESM) forming the core of this new simulation integration framework.

The IESM is designed as a composition of core services that builds an information broker for data-intensive multi-modality systems and their simulations, simulators, and synthetic environments needed for testing, training, and analysis. The derived requirements include the following: the ability to interface with live systems; to provide key simulation services for time management, communications, and data transformation across multiple scenario domains in a variety of atmospheric conditions; to allow simulation configuration and orchestration (without the need to involve a simulation specialist) facilitating data collection and analysis; and to enable multi-level security (MLS) solutions to support localised and distributed simulation operations with partners and allies.

To implement such a scalable, flexible, adaptable, modular, and configurable simulation infrastructure, MITRE identified the use of composable services as best practice. The justification for this decision, considering these characteristics, can be summarised as follows:

- Depending on the size, scale, or number of simulated entities and participating services, or the amount of data to be exchanged, the number of services providing the needed functionality can vary. Composable services allow engineers to add or remove services as needed.
- Different service instantiations can provide similar functionality to services that have different resolution/scope, time management needs, and supported simulation paradigms.
- Should new or unforeseen conditions occur, only those services affected by those conditions need to be updated, allowing rapid and efficient adaptation of the solution to the new environment, tasks, missions, or threats.
- Services are modular by design, allowing them to be separated and recombined by engineers, based on the principles of loose coupling in the technical domain and composability in the conceptual domain.
- All properties captured so far are leading to a fully configurable solution that provides all needed functionality in an efficient way.

In the following subsections, we introduce the categories of services belonging to the IESM. These are core services providing the information broker functionality, common services that enable fair fight within the composition of services, and exercise services that provide help in setting up, running, and evaluating the simulation event. The existing simulation systems are interpreted as services as well. As they are interconnected via the IESM, they are referenced as edge services. They provide the functionality needed for training, testing, and analysis by military users.

Figure 3 illustrates these four categories of services. Based on our research, we consider the set of core services to be stable, meaning we do not foresee additional core services to be required. However, if future research reveals the need for additional core services not thus far discovered, these can also be integrated into the IESM. The common services and exercise services depicted are only a subset of possible services of these categories, and additional services can be added as needed. When conducting a training exercise, the support needed will differ from running an operational test, so a different set of exercise services can be configured and composed. Furthermore, analysts may have preferred tools they like to use, so that the integration of such tools as an exercise service should also be supported. Finally, the edge services in the figure are only exemplary placeholders for the wide variety of simulation systems that can provide the requisite functionality for any given use case.

2.2.1 Core Services

The initial design focused on the definition of a set of core services that implements the information broker functionality needed to execute a composition. The influence of the concepts provided by the HLA RTI are

clearly visible. However, these original groups were modified and extended to address the challenges more effectively. The following seven service categories were identified as core services for the IESM:

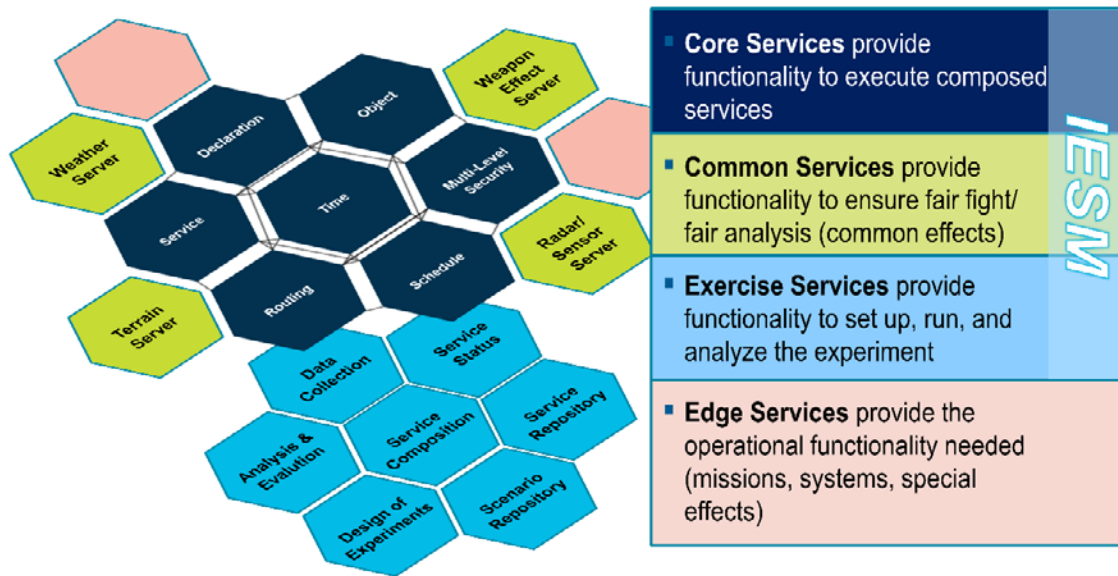


Figure 3: Information Exchange Services Matrix and Supporting Services

- *Service management:* These services provide information on which simulation services are accessible and online (i.e., currently participating in an ongoing exercise). If necessary, the IESM can launch more than one service manager to provide other IESM services with status information on services that could potentially participate, scaling to the number of participating edge services.
- *Declaration management:* These services provide information on which components will produce and which will consume information objects to be exchanged, and which operationally relevant services the IESM provides to the simulated operation. They work closely with service managers and allow them to initialise publish-subscribe, push-pull, and alternative information exchange methods, based on availability and interest.
- *Object management:* In contrast to declaration management services, these services supply information on simulated objects that are currently shared, including which edge service initiated the object and which service is currently in charge of such distributed information objects. These services also provide transient storage for information objects that are used frequently and should be provided immediately to a requesting service if the operation is time critical. They also perform data mediation services. Several object managers may be needed to scale the IESM to the desired number of simulated objects.
- *Time management:* These services synchronise the execution of all participating simulation services, including services that operate faster and slower than real time. The details go beyond the scope of this paper. Instead, we refer to other publications, such as [12].
- *Routing management:* These services enable the transfer of tailored data between participating services via configurable communication channels. The services ensure that only required information is submitted, and only information that is not already available in the transient storage is requested from the producing simulation service. Routing managers can scale and adapt to the number of required routes and constraints for such routes. The concept of multiple parallel but

synchronised routes is new to the simulation community, and has not been addressed in any of the current simulation interoperability standards.

- *Schedule management:* When operating in high-performance environments, it may become necessary to adapt the order in which simulation and IESM services are executed and to produce required information objects to ensure real-time availability. Schedule managers address this challenge. In addition to knowing the technical state of all participation simulation services, these services may also require mission awareness. The topic of variable scheduling has also not been addressed in current simulation interoperability standards.
- *Multilevel security management:* When simulation services and audiences with different security classification/clearance levels participate in the same simulation experiments, the accessibility and visibility of data and services depend on user role and clearance/classification level of the user and/or service. By obfuscating and filtering/masking information objects and service performance accordingly, these services provide cyber security against illegal access or modification of the configurations and data.

Conceptually, all these services collaborate with each other to deliver precisely the required information to each endpoint, without any extraneous traffic, in a secure and timely manner. In addition, if a simulation or experiment does not require certain functionality, the service providing it will not be loaded. The new infrastructure will only provide the required functionality at the specific point of need, such as geographically distributed simulation centres all supporting a common exercise. Higher functionality, such as data mediation facilitating the information exchange between participating simulation systems (that may have different views on the information being exchanged) can be provided as an interplay of these services. The technical solution applied for our proof of feasibility is documented in section 3.1 of this paper.

2.2.2 Common Services

The second category of services belonging to the IESM is common services, which are based on a concept well-known to the NATO M&S Group. Common services provide functionality required by several participating simulation systems, such as common weather, terrain, or weapon effects, for example. A recently presented NATO example for providing such common services is presented in [13].

The reason for common services is to ensure fair fights between simulated entities in different participating simulation systems, by ensuring the consistent computational representation of effects [14]. Instead of using the various implementations as provided by the original simulation systems, a common implementation is used instead. Otherwise, the result of a fight may differ, depending on which simulation system computes the effect. If such calculations result in systemic preferential treatment for any one side, the fight between the entities would be considered unfair and not suitable for training, and even less so for analysis. Common services mitigate this imbalance by replacing some functionality provided by the individual simulation services with a common conceptualisation and implementation of that functionality. Therefore, the use of common services will likely require potentially significant code changes in the participating simulation systems, especially for legacy systems with a monolithic code structure. Modular systems may be easier to adapt.

In the context of NATO, it should also be pointed out that common services should not cover up national doctrinal differences and variations. If a mission's outcome depends upon the applied techniques, tactics, and procedures, these differences must be considered while planning training, analysis, and testing events. The intent is to eliminate systemic unfair fight combinations resulting from artificialities within the composition, not to de-emphasise any real-world variations.

2.2.3 Exercise Services

The third category are the exercise services. These are ‘custodian’ services needed to set up, run, and evaluate the simulation event. Although not needed for the execution itself, this set provides important practicality for military users. The exercise services facilitate and simplify the administration of this new infrastructure by providing intuitive interfaces and abstracting the complex technical details.

Exercise services must support exercise planning, preparation, execution, and assessment. They provide the information required by the exercise control group, as well as by simulation and network engineers. The current simulated scenario (and the various perceptions thereof by exercise or test participants) is as important as the current workload in the computer systems’ execution of the simulation and the bandwidth availability of the underlying network. All data of possible use during the execution shall also be accessed and stored for after-action reviews, in an operational sense (i.e. providing better training and tests), as well as in the technical sense (i.e. providing technically stable and efficient solutions).

Therefore, exercise services should provide a framework that allows the integration of all services needed to support the simulation experiment, including the use of operational data where desirable and possible within classification constraints. The military training and test communities already apply comparable solutions providing such functionality [15], but often not in the scalable, flexible, adaptable, modular, and configurable way envisioned for the next generation of the simulation infrastructure.

2.3 Applying the Concept of Composable Services

The concept of composable services is also applied to the core, common, and exercise services of the IESM to maximise reuse of applicable solutions already provided. This includes using operational planning tools to plan and initialise simulation experiments. The planner responsible for a training or testing event should not have to be concerned with the simulation infrastructure, but should be able to design the mission underlying the training or test with the tools they are used to working with.

The concepts of composable services should also allow the reuse of parts of current infrastructure solutions—such as services providing functionality needed for time management—that can be based on RTI implementations, or to reuse particularly successful after-action-review tools. Software engineering provides numerous solutions to make successful solutions web-accessible as services, and several research projects in support of the idea of M&S as a service have been conducted by NATO [9].

Therefore, concepts presented in this paper are more of an evolutionary (rather than a revolutionary) new approach and allow the transition from current implementations towards the new simulation infrastructure needed to support the new systems engineering challenges, such as those captured in [7].

3.0 ADDITIONAL CHALLENGES

An implementation of the concepts of composable services must overcome some additional challenges that we will address in this section. Some are technical, such as the selection of an appropriate method and technology to couple the services; others are conceptual, such as providing a common conceptual understanding of the mission to be supported in the training or testing exercise, allowing for the conceptual alignment of providing services, or the avoidance of epistemological or hermeneutical mistakes in the assessment of the exercise or training event.

The following section provides a selection of challenges for consideration, which is neither complete nor exclusive.

3.1 Service Coupling

As discussed in the earlier sections, one of the driving requirements for the JSE is to utilise distributed, modular, composable architectures that leverage many purpose-built components simultaneously, rather than one monolithic simulation engine that drives the entire system. It has already been noted that such architectures pose significant challenges concerning scalability and integration. As a response to such challenges, MITRE has developed the *LightBind* Framework as an example of how to loosely couple services efficiently. *LightBind* is designed to let developers quickly build applications that need to integrate with many other heterogeneous hardware or software components, both local and remote. It serves as an ‘Application Programming Interface (API) Aggregation Engine’, which wraps the functionality of those components with a series of lightweight ‘drivers’ and brings them all into a single environment. This allows for real-time metrics collection, event notification, and functionality invocation without any modification of the original components. It includes a platform and language-agnostic set of interfaces and libraries; support is currently included for both Windows and Linux systems, with software development kits (SDKs) for C++, .NET (C#), and Java components.

LightBind utilises three distinct entities in its framework: drivers, a server, and the agent, as visualised by the simple example presented in Figure 4:

- *LightBind Drivers* are the fundamental atoms of the framework. They are wrapper programs that convert the existing API of disparate software and hardware resources into a common standard that can be accessed by other components. They allow the integration of applications or resources via their native API as well as non-executable binaries, such as dynamic link libraries (DLL) or Java archive (JAR) files. The driver interface specification allows developers to expose their components’ functionality as regularly measurable metrics, discrete notable events, and remotely invocable functions. Drivers can be simple, stateless translators or deep, complex programs depending on the use case. As they are only tied to each software or hardware component, they are meant to be reusable across organisations for different experiments or simulations.
- The *LightBind Server* is the central control and monitoring application, providing a single endpoint for the administration and analysis of the entire environment, down to the raw infrastructure level. The server is not one common application that is run in every environment; rather, it is purpose-built by each organisation and tailored to their specific needs. Its nature is dependent upon the organisation’s use case. Thus, it can be a web application, a desktop application, a mobile application, or even a rich and dynamic web service with a complete authentication, logging, and database backbone. The *LightBind* Software Development Kit (SDK) provides everything developers need to quickly and efficiently implement their own server programs in the form they require.
- The *LightBind Agent* is a background service that is installed on each machine involved in the activity. It serves as the gateway for that system into the *LightBind* network. The agent manages the locally-installed drivers and exposes them to the server. The server can connect to many agents across many machines, explore what drivers are installed, and use the agents to instantiate any drivers required by the users during experimentation and operations.

The *LightBind* approach can be used to couple services that do not need any time management, and that agree on the meaning and use of information exchanged between the systems. As such, it can be used by itself to couple simulation systems without any additional infrastructure, if the real-time paradigm is followed and a standardised information exchange model is used (such as the protocol data units (PDU) defined in IEEE 1278, or an agreed federation object model (FOM) defined in IEEE 1516).

In practice, engineers within the MITRE team were able to use this approach to successfully couple DIS capable real-time simulations and simulators in only a few days.

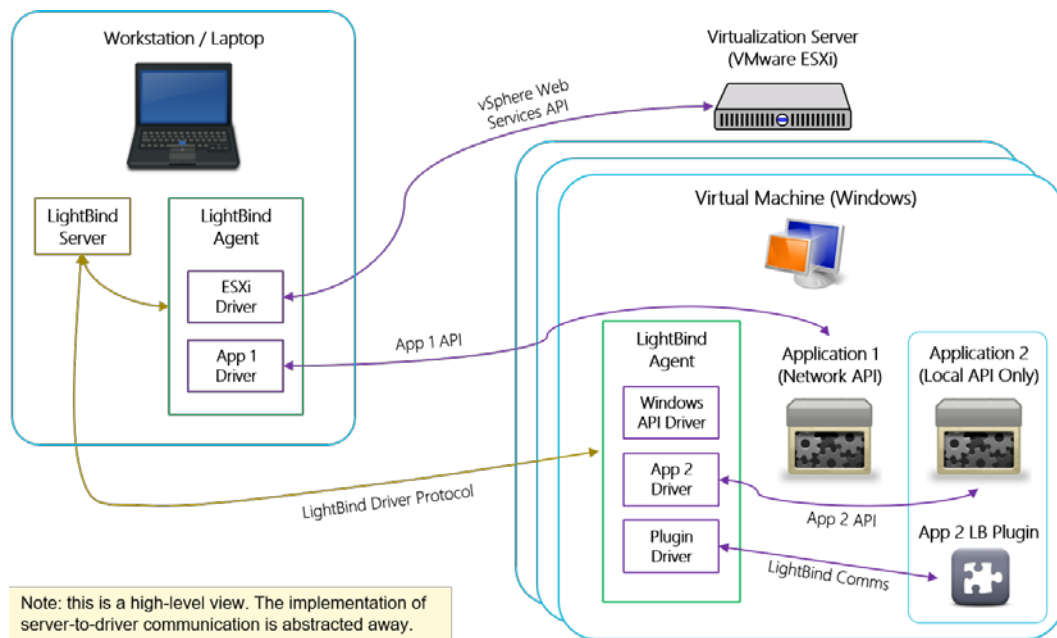


Figure 4: *LightBind* Framework Components

Its true potential is revealed when *LightBind* is used as a meta-framework, in which each IESM service and the edge services are connected via their respective drivers. As these services are loosely coupled, exchanging services is easy, as the only requirement is the registration and deregistration of the drivers from the agent. In addition, the approach does not assume a given number of services. If many simulated objects need to be exchanged, the amount of IESM service required to support the object management can be easily scaled. If the composition is distributed locally, IESM services can be provided locally and synchronised with each other, thus addressing (for example) the time challenges identified in [16].

The *LightBind* approach is not mandatory but is presented as an example of a promising implementation approach. The concepts presented in this paper can be implemented by various approaches, as long as they provide the required exchange of information between the services. *LightBind* is an example of new technology applied in the current prototypes and provided the desired technical maturity and flexibility.

3.2 Conceptual Alignment

The principles and concepts discussed thus far have focused on developing and providing a simulation infrastructure mainly concerned with *interoperability*, which we define as *the ability to exchange data and make use of these data* in the receiving system or service. As discussed in [17], interoperability is necessary but not sufficient to support fair fights for training and analyses. This requires *composability*, which we define as *the consistent representation of truth* in all participating systems, which can be enabled by conceptual alignment of services that are used to simulate the diverse aspects of a mission. The use of common services, as defined in section 2.2.2 of this paper, is the ultimate solution. However, as this may require significant changes for edge services, the following solution can be applied as an interim solution. The central idea of conceptual alignment is to use the military planning process for a mission needed to provide the contexts for the training or test event as the reference model for what the different edge services and applicable common service must provide.

- In the conceptual planning phase, the military planners define the mission, including metrics for success. Planning can be conducted with operational mission planning tools as well as with alternative planning tools, such as discussed in [15]. The mission can also be captured in operational

standards, such as System Modelling Language (SysML) constructs, as used in the NATO Architecture Framework (NAF) or the DoD Architecture Framework (DoDAF).

- In the composition phase, the edge services and common services that can provide needed simulation capabilities to represent systems and activities required to conduct the mission (including opposing forces) are identified. Applying user-defined optimisation rules, the services that are the best composition to simulate the full mission are then selected. The mission information is enriched by data about the providing service, package information including interfaces and other details for the providing services, and more. The mission data enriched by the technical information becomes the blueprint for the next phase. As the blueprint is derived from the mission, the operational requirements for training and testing are fulfilled.
- In the operations phase, services are composed to implement the blueprint. IESM and edge services are adapted and scaled to fulfil the technical requirements for training and testing. By orchestrating the composed services, the event is conducted, and the results captured and evaluated. The assessment provides feedback to improve operational ideas as well as technical modifications for future events.

Figure 5 presents this Concept of Operations to ensure conceptual alignment of services by ensuring that the mapping from mission to blueprint to implementation by a service is unambiguous and well documented.

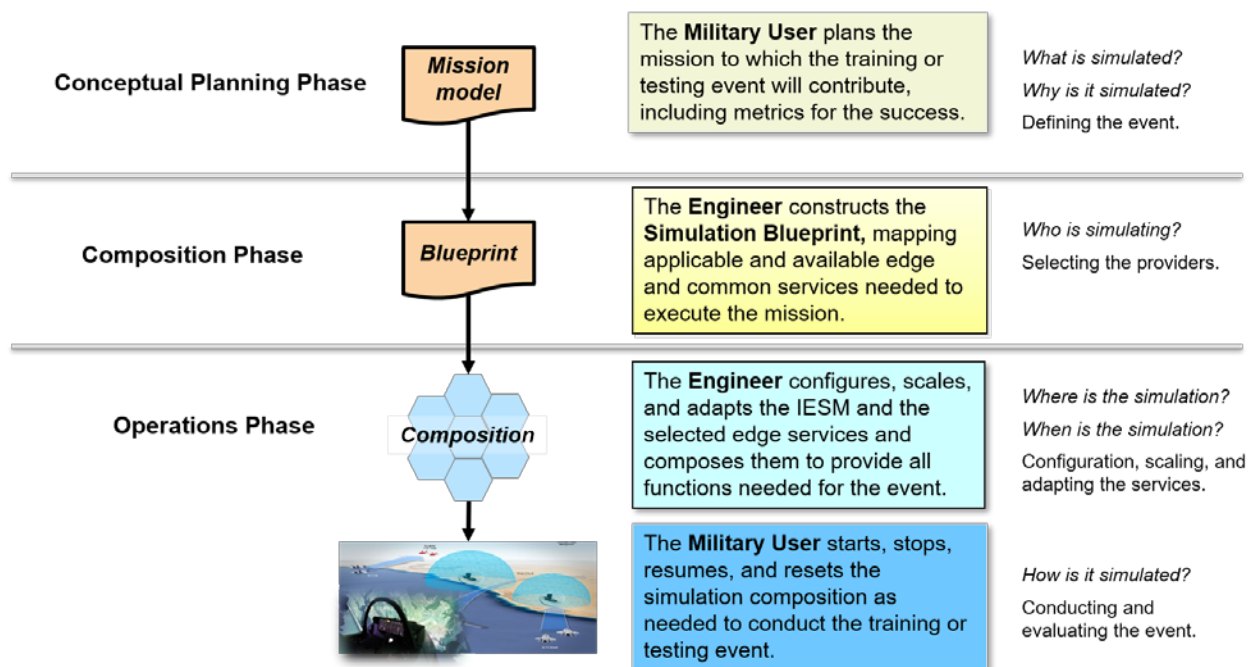


Figure 5: Concept of Operations

In practice, services supporting these different phases can be composed to modular and configurable supporting solutions, such as scenario generation tools, including operational solutions already used in the operational context, in the conceptual planning phase, or network configuration tools and workload monitoring tools used for the operations phase.

3.3 Epistemological and Hermeneutical Challenges

When assessing simulation results, two general risks must be avoided. These can be encapsulated in two key

questions, namely (1) ‘Do we simulate everything important for the training or test event?’ and (2) ‘Do we base our assessment exclusively on unbiased, simulation-based data?’

The *epistemological* challenge centres on the limits of an experiment that stem from the conceptual model of the mission: Does the mission model capture all relevant concepts, properties, relations, and processes? Does the mission model capture them at the correct abstraction level? Because the conceptual mission model describes the ‘reality’ to be captured in the simulation (and used as the blueprint for conceptual alignment, as shown in the previous subsection), only concepts included in the model can be evaluated. If important aspects are overlooked, the simulation systems cannot take them into consideration.

The *hermeneutical* challenge centres on the interpretation of the results themselves. When interpreting the results of a simulation experiment, engineers must be guided by the conceptual mission model underlying the experiment. It is human nature to interpret results in the light of one’s favoured worldview, often resulting in unconscious bias. Interpretations should only use assumptions and constraints that are captured within the conceptual model, because all other explanations extend beyond the simulation experiment and consider concepts outside the model’s scope.

Epistemological and hermeneutical challenges further emphasise the role of the mission/blueprint artefact used for conceptual alignment, not only for the technical implementation, but also for the assessment and documentation of results. Having a clear and unambiguous representation of the conceptual ideas of the mission that supports the testing and training event is necessary for success. If this is achieved using formal methods that clearly capture all desired entities, properties, relations, actions, and effects, it is then sufficient for the agreement at the conceptual level.

4.0 DISCUSSION AND SUMMARY

Systems engineering developments in IoT and CPS domains result in systems that utilise significantly more data than current approaches, and expose multi-modality. Current simulation interoperability standards (such as IEEE 1278 and IEEE 1516) potentially fall short in supporting the resulting information exchange requirements for simulation systems representing such new systems. The next generation weapon systems of NATO are not an exception.

As IEEE 1516 does not standardise the implementation of an RTI, but rather its interfaces and the required functionality, there have been various efforts to web-enable the RTI as described in [18]. However, as the service groups were too tightly coupled, separating and individually configuring them while remaining compliant with the standard proved to be challenging. While time management [12] was the state-of-the-art, the data-rich and multimodal systems presented unforeseen challenges that ultimately resulted in the providing technology being perceived as insufficient for these new systems engineering environments by practitioners. Thus, instead of using standardised solutions to foster reuse and collaboration, engineers focused on highly efficient point solutions driven by the requirements of individual programs, which carries the risk of resulting in the same fragmentation and isolated-island solutions the community has sought to avoid with the introduction of standards.

As a future option, this paper proposes a scalable, flexible, adaptable, modular, and configurable simulation infrastructure based on common, core, and exercise services, comprised in the IESM as a central piece of a possible JSE. The services can be loosely coupled to maximise flexibility and scalability, as demonstrated using the *LightBind* framework. While this provides a solid technical solution representing the state-of-the-art, the unambiguous and formal representation of the simulation purpose is necessary and sufficient to ensure the challenging conceptual alignment of independently developed solutions. Representing the simulation purpose (such in military scenarios) in form of a formal and machine-readable description of the mission makes all design decisions traceable and avoids misinterpretations in the evaluation and assessment

process. It also conforms with the IEEE 1730 Recommended Practice for Distributed Simulation Engineering and Execution Process (DSEEP).

This proposal is not the end of the road. The research is driven by the dichotomy between the need for highly efficient support of exercises and the support of reuse through standardised approaches. Highly efficient solutions do not include any unnecessary ‘dead weight’, (for example, mediating data into or out of the information exchange format, providing multi-stage translation from standardised interfaces to the really needed interfaces, or providing information required by the standard not really needed for the actual connection). As a result, they are often so specialised that they do not qualify for reuse in any other context, and they require qualified experts to maintain them. Standardised solutions are always a compromise between efficiency and reusability.

The concepts presented in this paper relate to the use of composable, configurable, adaptive services for the IESM as well as the JSE itself. This provides a modular and easily scalable solution, as services can be loaded as often and where they are needed—and only loaded if needed—reducing ‘dead weight’ significantly. However, as model-based systems engineering (MBSE) methods increase, it will become more likely that future standards will be applied at the modelling level, and MBSE methods will derive highly efficient solutions from this meta-alignment of underlying concepts. Although research has already been conducted in this domain, the resulting technologies are not yet mature enough to be applied on the scale required to support JSE or related efforts. Nonetheless, the community should continue to observe and apply these ideas in experimental set-ups, as the auto generated production of highly efficient solutions (based on common standardised meta-models for the aligning of data, harmonising of processes, and orchestration of the composition) offers a promising future solution.

Although the examples here are from the defence simulation domain, the proposed new simulation infrastructure is generally applicable across all domains for simulation systems. Using loosely coupled services (composed on the basis of unambiguous and formal representation of the simulation purpose) combines the openness of IEEE 1516 with the semantic and pragmatic rigour of solutions that prescribe the use of a common object model as the centrepiece of their agreements (such as the object bus used in TENA, or the use of clearly standardised IEEE 1278 PDUs). At the same time, valuable lessons learned can be applied, and solutions that can be transformed to services (for example by using the *LightBind* approach) can be reused. As such, the proposed solution should be of interest for future collaborations within NATO as well.

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Virtual Reality CBRN Defence

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ABSTRACT

Over the past decade, training in virtual reality for military and disaster preparedness has been increasingly recognized as an important adjunct to traditional modalities of real-life drills. However, there are only a few existing solutions that provide immersive virtual reality training and improve learning through an increased amount of presence. In this paper, we present a novel and flexible Virtual Reality (VR) training system for military and first responders that enables realistic multi-user training in large environments. We show how the requirements of peer stakeholders for disaster relief with an explicit focus on CBRN disaster preparedness transfer to the concept, current implementation and future features of our system. The development and integration of multiple technologies allows a wide variety of interaction and collaboration within our immersive system. In addition, we demonstrate the training capabilities of our proposed system with a multi-user training scenario, simulating a CBRN crisis. Results from our technical and user evaluation with 13 experts in CBRN response from the Austrian Armed Forces (National Defence Academy & Competence Center NBC Defence) indicate strong applicability and user acceptance. Over 80% of the participants agreed “much” or “very much” that the presented system can be used to support training for CBRN-crisis preparedness.

1.0 INTRODUCTION

Effective training is a cornerstone of disaster preparedness. Quality, consistency and frequency of training are shown to impact self-perceived disaster readiness of first responder units. However, barriers such as time, cost and safety limit the extent to which large groups of responders can be brought up to established standards, particularly related to integrated disaster team response skills and experience. This is particularly evident during events involving large-scale mobilization of population-based healthcare and public health resources, where skills learned through training impact directly the actual response. The advent of technologically-based approaches through Virtual Reality (VR) environments holds significant promise in its ability to bridge the gaps of other established training formats.

The training of professionals to face emergencies requires the mastery of several skills and abilities that need practice. However, facing real emergencies should be avoided during the initial stages of training. Instead, training should be provided under guidance and in a controlled setting that mimic real-life situations as closely as possible. VR integrates real-time computer graphics, body-tracking devices, visual displays and other sensory inputs to immerse individuals in computer-generated virtual environments (VEs). VR creates an illusion in the user of being physically inside the virtual world, and this sense of presence can have

positive effects on task performance, enabling the learning situation to be experienced as a real context, which in turn promotes experiential learning. Indeed, VR enables individuals to learn by doing, through first-person experiences. Virtual Reality provides a tool for developing instruction along constructivist lines and an environment in which learners can actively pursue their knowledge needs. Another important characteristic to highlight is the possibility of self-learning and over-learning provided by these tools, since trainees can repeat the situation as many times as they want. Such activity is in part guided by the trainee, which promotes the development of operational and formal thinking by facilitating the exploration of different possibilities. This kind of training method can be readily adapted to the trainee's pace, timetable and needs. In addition, these tools enable the difficulty of the problems to be solved to be graded, thus facilitating learning by bringing subjects progressively closer to the solution.

Over the past decade, VR-based training in crisis preparedness has been increasingly recognized as an important adjunct to traditional modalities of real-life drills. Multiple studies, i.e. [1]–[4] have highlighted VR applications in disaster training. Many government agencies have adopted until now VR-based training. However, existing solutions mostly offer desktop-based VR training that lacks visual 3D immersion and navigation by natural walking. Both factors reduce the sense of presence. Furthermore, natural walking is essential to simulate stress and physical excitement, which is of particular interest to create a realistic training for on-site squad leaders and rescue teams. There are only a few existing solutions that provide immersive VR training through stereoscopic 3D scene viewing and body motion analysis, e.g. [5], [6]. However, these systems are solely designed for military training, they are very expensive (more than \$100.000) and require extensive technical knowledge for system setup. These factors heavily diminish their applicability for crisis training of first responder agencies since they require a flexible immersive VR system to enable multi-user, interdisciplinary team training at different command levels in various training scenarios.

As the first step towards a flexible multi-user VR training system, we performed a thorough analysis of the state of the art of existing VR training systems [7], [8]. Furthermore, we analysed the requirements of two peer stakeholders with a focus on CBRN crisis and disaster preparedness.

Subsequently, from these analyses we have drawn conclusions if - and to which extent - current technologies satisfy the essential stakeholder requirements. Furthermore, we have integrated suitable technologies in our system and - where no suitable technologies were available - developed novel approaches. We assessed our system in a user-study with 13 users, the results of which we present in this paper. Finally, we outline future research steps.

To summarize, the paper presents the following contributions:

- Summary of a requirement analysis for CBRN defence VR-training
- Presentation of the concept for multi-user training system based on stakeholder requirements
- Implementation of a demonstrator VR system
- Results from the evaluation of our system in a user-study.

2.0 RELATED WORK

Employing VR technology to train first responders and relief units is an ongoing research topic for about two decades [9] and has led to the development of several academic, military and commercially available systems. The aim of the following state of the art analysis is to describe internationally available VR training systems, either providing training for military, first responders or civil purposes. To be able to evaluate the applicability of existing systems for providing interdisciplinary training of disaster relief units, we focus on analyzing virtual reality systems that are capable of multi-user training.

Thus, we did not study systems that only provide single user training, systems to train negotiation & language skills (i.e. *Bilateral Negotiation Trainer - BiLAT*), or systems that enhance live exercises in outdoor environment (i.e. *Augmented Reality Software* by ARA - Applied Research Associates). Furthermore, we did not study in detail systems that solely exist as prototypes. However, as some of them show significant potential for future disaster preparedness training, we briefly summarize interesting projects. *Immersive Video Intelligence Network (IVIN)* [10] is a tool offering 360° building walkthroughs that are visualized on a mobile device's display. The buildings' interior is produced from photos and is supposed to enhance the indoor situational awareness of first responder units. It does not provide an immersive setup, natural walking for navigation nor training functionality. *Sportevac* [11] is a desktop-based virtual training scenario simulating the challenges of a stadium evacuation with thousands of avatars, and the *Virtual Terrorism Response Academy* [12] is a desktop-based and non-immersive VR environment that aids trainees practicing various terrorism threats such as chemical hazards. The system *Enhanced Dynamic Geo-Social Environment (EDGE)* [13] is a VR platform with the major goal of enhancing first responders' communications and coordination while also making training more efficient and cost-effective. EDGE provides the creation of a dynamic, scalable and customizable training environment and supports multi-user training in a desktop-based, non-immersive virtual environment using a high-quality game engine for rendering, a standard screen for visualization and keyboard and mouse for navigation.

In the following, we outline the results of our state of the art analysis of available multi-user VR training systems. We categorized the systems into applications that either 1) provide pre-defined scenario(s) to train multiple users, or 2) allow the creation of various, self-defined scenarios that can be subsequently used for multi-user training. For pre-defined scenario systems, we provide an overview as they demonstrate well the potential of VR training. However, we will not go into all details of each approach as the pre-defined scenario systems lack out-of-the-box functionalities to create self-defined training scenarios with arbitrary devices, i.e. by providing open and accessible hard- and software interfaces. Thus, we describe in detail multi-scenario training systems as they might act as technological base to create immersive multi-user VR training systems for disaster preparedness.

2.1 Single Scenario Training for Multiple Users

A large number of simulators using VR technology exists to train military personnel for specific air, land and naval operations. Especially training of aircraft personnel has a long history, resulting in more than 1600 military aircraft simulators up to date that are in service worldwide [14]. The most compelling simulation is provided by Full Flight Simulators (FFS), such as the *Navy MH-60 Romeo* or the *Eurofighter Aircrew Synthetic Training Aids (ASTA)* that comprises a Full Mission Simulator (FMS) and a Cockpit Trainer/Interactive Pilot Station - Enhanced (CT/IPS-E). In addition to simulators for aircraft on-board training, a number of simulators exists to train Unmanned Aircraft Systems (UASs), i.e. the *Predator Mission Aircrew Training System (PMATS)* or the *MQ-8 Fire Scout Unmanned Helicopter*. Since these systems are not of our primary interest for disaster preparedness training, we do not present more details.

For military operations at land, VR simulators exist to train gun handling, shooting as well as tank operations. The *Simulated Weapon Environment Testbed (SWeET)* [15] targets at small arm weapon design and testing. It uses five 2D screens to project a 300° view of indoor or outdoor scenarios with customized weather conditions, locations and times of day. At each screen, up to four users can perform the exercise. The *Small Arms Trainer with 180 Degree Visuals (180SAT)* [16] aims at training of marksmanship skills, situational awareness and reaction times to increase the effectiveness of trainee usage of weapons in realistic threat scenarios. The system comprises large 2D projection walls and screens that are configured for individual and two-person team training. To train handling and operation of tanks, various systems exist, i.e. the *Leopard Gunnery Skills Trainers (LGST)* [17]. It is a self-contained, standalone system to train Leopard 2A4 crew commanders, gunners and loaders. Therefore, it provides at least six desktop-based workstations and one Driver Station Simulator (DSS) to enable multi-user tactical training at platoon level. The DSS simulates the tank interior with actual hardware and allows the driver to take part in the tactical training.

Each workstation is equipped with multiple 2D screens, headset and microphone for communication as well as mouse and keyboard for interaction.

Besides training in the aforementioned environments, also systems for exercising naval operations exist, i.e. the *Visual Bridge Simulator* [18] that is used to train all warfare branch officers, except aircrew, for the entire range of watch keeping, ship-handling and navigation at different command levels. Another example is the VR Team Trainer [19] (also named *Cooperative Computer Based Training* by the German Armed Forces) that aims at exercising control, operation and usage of complex systems such as M3 amphibious vehicles. Therefore, the trainees' task is to couple together amphibious vehicles, boats and floating bridge elements in a waterway to form ferries or bridges. Before simulation start, the trainer can configure scenario parameters such as current speed, visibility and wind velocity. The hardware setup comprises a desktop-based VR system, consisting of three to four user workstations, a gesture recognition workstation, a trainer workstation, a shared view workstation and a vehicle simulator. The user workstations are equipped with 2D screens, headset, microphone, keyboard and joystick, the gesture recognition workstation provides a keyboard and a data glove to capture hand gestures. The vehicle simulator offers a 360° projection combined with force feedback for realistic vehicle simulation.

The presented systems cover a wide range of training scenarios and outline the application of VR systems for real-world training tasks at different command levels. However, they share the limitation not providing out of the box accessible hard- and software interfaces to extend the systems for disaster preparedness training.

2.2 Multiple Scenario Training for Multiple Users

To create multiple scenarios for training of multiple users, there has been active development by industry, both offering VR training systems for military as well as civil usage. The amount of immersion provided by the VR training systems range from non-immersive desktop-based to fully immersive environments.

2.2.1. Non-Immersive VR Systems

The software framework Virtual Battle Space 3 [20] offers training of unit tactics, techniques and procedures in decisive actions for soldiers. Its open software platform enables 3rd party products to extend the simulation environment and functionality. To create self-defined training scenarios, it offers several built-in applications, including mission editors, an after-action review module, a development suite, a 3D content creation module including a model library and a modeling tool. The mission editor module comprises an offline editor to create scenarios at air, land and sea, to prepare terrain, objects, avatars, vehicles, weather (i.e. weather, sun, and time of day). The real-time mission editor enables the trainer to influence the scenario during training. With the help of the after action review module, post-training analysis can be conducted with the ability to visually fast-forward or rewind to events. Amongst others, it tracks statistics on casualties, engagement time and rounds fired and provides trainers and trainees to view the scenario from different perspectives including 3D, 2D, and from any trainee's perspective. The real-time 3D simulation is based on the game engine Real Virtuality 3 combined with NVIDIA PhysX. The network module is optimized for a large number of trainees (> 100) and enables to interconnect several Virtual Battle Space servers together or connect with other military simulations.

Out of the box, Virtual Battle Space supports standard workstations for each user with 2D monitors, keyboard and mouse as well as headset and microphone, resulting in a non-immersive desktop-based VR setup. It is used by a number of armed forces worldwide, including the U.S. Army, U.S. Marine Corps, UK Ministry of Defence, German Armed Forces and NATO. Due to the open software framework, it is furthermore used as base technology for a number of training tools, i.e. *Unmanned Aircraft System Training (UAS-TS)* for tactic drone LUNA (eurosintec GmbH for German Armed Forces) and the *Leopard Gunnery Skills Trainers*.

The system XVR - Virtual Reality Training Software for Safety and Security [21] aims at training and exercising of emergency response professionals. It offers education, training and assessment of incident commanders of operational level up to strategic level, i.e. for members of relief units from emergency services, industry and critical infrastructure. By default, it offers single or multi-user training in a networked environment based on standard computer hardware, using a workstation, 2D screen, keyboard, mouse and joystick. Its software framework offers an editor for rich 3D content creation. The editor allows the configuration of region, incident or disaster scene as well as the determination of incident type, scale and location. Further incident parameters - i.e. number of rescue vehicles, personnel on call - can be customized, forcing the trainees to take into account logistic aspects such as call-up and transport times. During simulation, the trainee uses the joystick to navigate around the environment (walk, drive, fly) to assess risks and dangers of an incident. The trainer can give live feedback and can respond to a trainee's decision by activating events in the virtual scenario. XVR provides the creation of specific assessment scenarios to create predictable and repeatable training environments for an unbiased assessment. The system is used by a number of companies, organizations and state agencies, including ExxonMobil/Netherlands, BASF/Germany, Mont Blanc Tunnel/France&Italy, London Fire Brigade/UK and Austrian State Fire Brigade School.

The Advanced Disaster Management Simulator (ADMS) [22] offers training for incident command and disaster management teams at all command levels. It provides a large number of modeled 3D environments to train in scenarios that simulate building collapses, plane crashes, crowd riots, or nuclear, biological and chemical hazards. The built-in scenario editor allows the configuration of generic, semi-specific or specific 3D environments, incident sites (type, scale and location) and incident specific parameters such as vehicle positions, time of day, precipitation, wind, visibility, condition of casualties, terrain, and traffic as well as bystander behavior.

For performance evaluation, ADMS provides an observation and scoring system and an after action reviewer that records the exercise. In playback mode, training staffers can start, stop, pause and fast-forward the exercise and look at the incident from any point of view. ADMS comes as a modular, expandable disaster simulation platform using proprietary hardware and software (operating system). Thus, specific workstations are required and must be individually purchased. For visualization, projection walls or standard screens are used while interaction is performed with several physical input devices, such as keyboard, joystick or driving wheel. Amongst others, the system is used by the New York City Office of Emergency Management and Netherlands Institute for Safety (NIFV).

2.2.2. Semi to Full Immersive VR Systems

Compared to the systems presented in Section 2.2.1, we will outline in the following systems that provides training in semi to fully immersive virtual environments. The *Advanced Network Trainer (ANTares)* [23], a system developed for the German Armed Forces, is a land, air, naval weapon system simulator for tactical training operations. Its system's most prominent feature is the modular cubicle hardware concept. It allows to couple multiple, individually equipped simulation cubes to create a networked environment for tactical mission rehearsal of complex operations or scenarios. The open architecture provides the integration of different systems to form a complex networked mission scenario. The cubes can be arranged as plug-and-play components in a customer-defined configuration. The hardware for visualization and interaction of each cube can be individually customized, ranging from off the shelf visualization and interaction devices (i.e. 2D screens, head mounted displays (HMD), keyboard, mouse, joystick, force feedback devices) to fully equipped maneuver stations with actual hardware. Internally, ANTares uses Virtual Battle Space (version 2.0) for 3D scenario creation, training simulation and debriefing.

The immersive VR system *Dismounted Soldier Training System (DSTS)* [5] offers training of dismounted soldiers of infantry platoons. One DSTS hardware suite comprises nine fully wearable and immersive VR setups (Virtual Soldier Manned Module - VSMM) for dismounted soldier training, five workstations for

multifunction soldier training, one staff control station and an after action review space. Each VSMM consists of a helmet with attached HMD, headset, microphone and an *Intersense InertiaCube 2+* for 3D orientation estimation of the head. For processing, rendering and networking, a notebook is attached to the soldier's vest that also accommodates another *InertiaCube 2+* for torso tracking. Additionally, a gun is provided, equipped with buttons for navigation and an *Intersense InertiaCube 3* for 3D orientation tracking of the weapon. The VSMMallows each dismounted soldier to stand, crouch, jump and lay during the exercise. Movement and thus navigation is done by button controls at the weapon.

At the software side, a content editor allows the creation of self-defined training scenarios incorporating semi-automated forces and the live participants. Scenario related parameters, such as movement of ground vehicles, aircraft, dismounted infantry, day time and weather effects can be configured. Built upon the commercially available *CryEngine* [24], the systems offers high quality 3D rendering with physics support. The system was developed by Intelligent Decisions for the U.S. Army and is available since 2012. According to the U.S. army, 102 test sites were planned in 2012 to be equipped with DSTS, costing \$500.000 for one suite. In 2014, Intelligent Decisions, announced the system *Medical Simulation* [25], a training environment for first responders. According to the provided specifications, the hardware setup is similar to DSTS, extended by biosensors to track gaze, blood pressure and heart rate. However, no information are giving regarding system availability or costs.

VirtSim [6] offers multi-user, fully immersive training for law enforcement situations as well as military tactic training at a squad command level. Therefore, it employs optical outside-in tracking (Vicon) to estimate the position and orientation of user's head, weapon and full body motion. This allows users to navigate in VR by real walking in larger sized physical spaces (20x20m). However, a plethora of Vicon tracking cameras is required to cover that volume making the system hard to setup and highly expensive. Off the shelf HMDs are used for stereoscopic 3D scene viewing that are connected to a user-carried notebook that performs processing, rendering and networking.

The *VirtSim* content editor provides a range of reconfigurable environments. For law enforcement, pre-defined scenarios exists for training of individuals in weapon discipline, making deadly force decisions, covering danger areas, team clearing techniques, use of cover and concealment, and communications among team members. Military scenarios comprises training of individuals in direct action, counter-terrorism and react to contact. An after action review module records trainees' body motions, shots, the individual manoeuvres of participants as well as team and squad manoeuvres. It provides playback of all actions and shots from every angle, and from each participant's perspective.

3.0 REQUIREMENTS

A requirement analysis was conducted by two peer stakeholders for disaster relief, the *Austrian Federal Ministry of Defence and Sports (BMLVS)* and the *Ambulance Team of the Red Cross Innsbruck, Austria*. Within this analysis, the interests and requirements of both stakeholders' CBRN defence elements were firstly identified. Next, scenarios were developed and described to derive demands to a VR training system. Within the scenarios, the stakeholders furthermore focused on specifying the involved command levels, the target groups and the required training content. For the full requirement analyses, please refer to [7], [8]. We briefly summarize the results in the following paragraphs and subsections.

To identify VR-relevant training parameters, the skill catalog for CBRN defence of the Austrian Armed Forces was used as base. Relevant skills were identified and subsequently reduced to skill bundles. At least three skill bundles with a high potential to be trained in VR were identified:

1. CBRN-defence recce
2. Urban search and rescue
3. Skills for aircraft rescue

Based on the identified skill bundles, three use cases have been derived that are described in more detail in the following subsections. All three use cases outline training scenarios that would be highly beneficial to be trained with a VR system. The focus is placed on the first scenario, which has been implemented in the current version of the system.

3.1 Scenario: CBRN Defence Recce

For this scenario, a virtual area of approximately 30x30km with a 24km airspace is required for the training of motorized and stationary elements.

The virtual environment should comprise a rural area containing some villages and infrastructure like bridges, power lines, railways or streets. This scenario aims at training of a CBRN defence recce platoon consisting of three specific vehicles and 28 staff members in different functions, such as platoon leader, squad leader, signal, driver, etc. Thus, at least 28 persons are directly involved in the virtual environment, requiring a multi-user collaborative VR system. The major mission tasks are:

- Observing
- Detection
- Decontamination

For the virtual simulation, it is necessary to customize the simulated hazard materials - i.e. chemical agents or radiological materials in various physical states - the weather conditions and time of day. Furthermore, it is required to move within the map, either within the entire map by controlling the virtual vehicles or by natural walking within a smaller physical volume (20x20m) for dismounted CBRN operations.

Furthermore, the virtual buildings can be entered and it is possible to communicate with the virtual bystanders in the simulated environment. For dismounted operations, the CBRN squad staff must be able to wear their actual defence protection suites, some additional equipment and radio sets. Amongst other, there are the following benefits employing a VR simulation to train this scenario:

- The scenario can be used for squad, group and platoon training/education as well as for single user training/education.
- The process of decision making can be trained as often as required for leaders of all levels.
- It is possible to visualize different areas, seasons and precipitation upon request. Furthermore, necessary tools and instruments can be virtually simulated.

In a real-world environment, providing all of the required infrastructure, participants and equipment for the intended training scenario is a cost and time extensive process, especially since there is a large amount of resources necessary. Furthermore, only a very small amount of hazardous material can be used for training since environmental contamination has to be avoided. Thus, using VR implies a tremendous potential to save costs and time, train the full range of hazardous material and provide training on a regular schedule.

3.2 Scenario: Search and Rescue

For this scenario, the virtual environment consists of an urban area, containing at least four to five buildings. Each two to four-story high building has a cellar and shows different damages caused by an earthquake. It shows a typical earthquake scenario with totally damaged buildings as well as medium and light damaged ones.

This scenario is targeted for training of the search and rescue elements of a search and rescue platoon. At least 45 soldiers are involved in the simulation at different command levels. So members of each command

level have to cover specific topics to collaboratively solve the major mission tasks:

- Exploration
- Searching
- Rescue of persons
- Clearing

For scenario creation, building structures (door entries, properties of staircases), obstacles and affected persons (amount, various injury patterns) should be straightforwardly to generate and customized. Furthermore, parameters such as weather and time of day should be adaptable. Compared to training in a real environment, there are the following benefits employing a VR simulation to train this scenario:

- Training and education of decision makers of all levels of a search and rescue platoon can be performed with this simulated scenario.
- It is possible to simulate medium earthquakes as well as large damages of the building structures.
- Various hazards can be simulated as well as number of casualties and the grade of injuries.

Upon decision making of a specific thread are rescue operations, a lot of different equipment is subsequently required and used on site such as generators, devices for drilling, crushing and cutting. However, we found no benefit to incorporate the training of their handling into the VR simulation due the following reasons. Firstly, a lot of quick ways to provide real-world training of these tools exist. Secondly, haptic and tactile clues as well as force feedback are important to train their correct handling. At the current state of the art of VR input technology, it is very hard or still impossible to mimic these tactile sensations in a realistic manner. Thus, we excluded equipment handling from this VR training scenario. To summarize, this scenario aims specifically at decision makers of all command levels and does not target (dismounted) personnel of a squad unit.

3.3 Scenario: Aircraft Rescue and CBRN Defence

This scenario aims at training of some specific CBRN-defence elements on military airfields. In case of an airplane crash, their priority is to rescue the pilots. This implies specific requirements to which these rescue units have to obey, such as arriving on the disaster site within 90 seconds and start firefighting within 2 minutes after the crash. Furthermore, the relief unit staff have to know all relevant parameters and specific handles of all aircraft types that are currently in use in Austria. A large number of different on-site hazards are possible such as explosives of ammunition, fuel and safety devices like ejection seats. All the safety devices depending on the various types of aircrafts must be known and correctly handled in case of an emergency to avoid false releases. Thus, the soldiers must be extensively trained to know by heart all necessary procedures. Therefore, drill training is often used.

This training scenario is not developed for decision making but for training of standardized procedures depending on the different airplane types. Thus, the virtual environment provides the trainees a training facility to improve their experience and handling on the basis of unlimited repetitions. Additionally, the virtual training scenario allows training in a virtual simulation of the different real airfields. Hence, trainees do not need to visit the various aircrafts in their real home bases, resulting in a reduction of time and costs.

3.4 Derived Requirements

In accordance to the developed scenarios there are some general and specific requirements derived. The general requirements were categorized as:

- Movement (virtual and physical)
- Manipulation of objects (virtual and physical)
- Communication
- Customization of Scenario Content & Parameters

The specific derivatives were categorized as:

- Specific Movements
- Specific Manipulations

For the scenario *CBRN Defence Recce* some of the necessary activities are listed below:

- Operate CBRN observation post
- Develop a weather report
- CBRN exploration

For each activity of all three scenarios the derived requirements were identified. One example is given in Table 1, which illustrates the identified derivatives for the scenario CBRN Defence Recce.

Table 1: Derived requirements of CBRN Defence Recce, showing in colour already implemented requirements and in grey functionalities planned for a future prototype.

Communication	Team communication (speech, signs)
	Team communication (radio)
	Communication to commander via radio
	Instruction to virtual person
Manipulation	Transportation of equipment
	Transportation of weapons
	Map consulting
Specific manipulation	Reading measurement results
	Use of binoculars
	Use of height level protractor
	Use of compass
	Filling in forms
	Writing of markers
	Sampling contamination on a flat surface
	Fixating marker (putting a stick in the ground)
	Skimming and Soaking up liquids
	Digging (up) ground material
Movement	Going
	Running
	Sitting in vehicle
	Lay on the ground
	Bend down, lay down
Specific movement	Mount/dismount vehicle
Customization of Scenario Content & Parameters	Hazard - chemical agent
	Positions (entry point and events)
	Weather (wind and visibility)
	Virtual persons
	Hazard - nuclear explosion

To specify these derived requirements, it was necessary to identify and describe the generic processes of each of the three scenarios. For instance, the search and rescue scenario consists of seven generic steps and the CBRN Defence recce scenario consists of seven activities. For each of the activities the content was formulated and analysed with regard to its applicability in a VR training application.

3.5 Technical Requirements

Based on the analysis of the stakeholders' requirements, the demands on a VR training system can be derived and summarized as follows.

3.5.1 Virtual Reality Objectives

The training environment should 1) be fully immersive to exploit the advantages of learning in VR, 2) provide 3D object interaction (selection and manipulation) with CBRN equipment and other mission relevant objects, 3) allow natural walking (and crawling) for navigation and to realistically simulate stress and exhaustion, 4) not limit the virtual movement range by physical space and 5) and be multi-user capable to allow for collaborative training.

3.5.2 Hardware Objectives

The immersive VR hardware setup should be 1) fully wearable, 2) quick to setup, 3) consisting strictly of off the shelf hardware components and 4) requiring a small amount of hardware to lower price and system complexity.

3.5.3 Software Objectives

The software framework should provide 1) creation of new 3D training scenarios, 2) level and terrain editor, 3) customization of scenario parameters before and during the training, 3) high quality 3D rendering with physics support and 4) after action reviewing for trainee evaluation.

4.0 SYSTEM DESIGN

We designed our system to fulfil the requirements described in the previous section. Figure 1 provides an overview of the overall system architecture. Horizontally we split the illustration in client (I) and server (II) modules. Vertically, starting from the top it illustrates the input devices (III), plugin-layer (IV), application-layer (V) and output devices (VI). Besides the different modules and sub-systems themselves also their integration stage is illustrated. Parts framed and written in turquoise are already implemented at demonstrator level, while entirely grey blocks show modules planned for future integration and implementation. Modules on the client-side are replicated with each additional user.

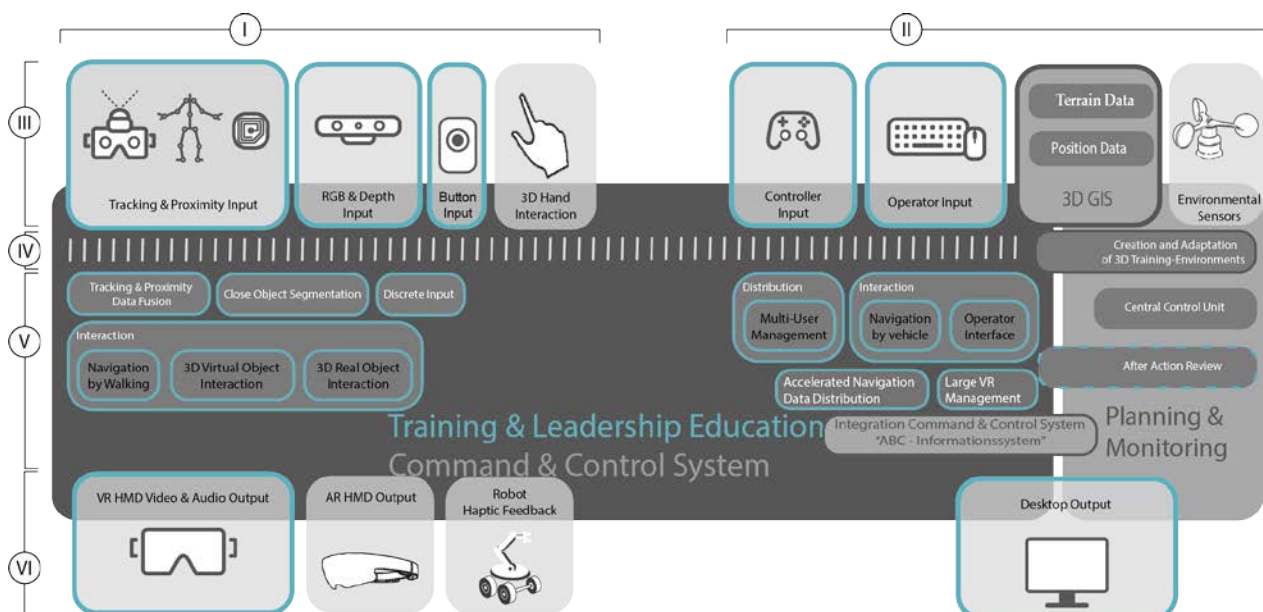


Figure 1: Schematic visualization of all modules and components of the VR client (I) as well as the server side (II) within our VR system. Input data (III) is forwarded through the plugin layer (IV) to the application layer (V), containing all application logic. After processing all data the visual, audio and haptic output is produced (VI).

4.1 Client

In the current demonstrator training at squad level is possible with up to four client VR setups, while the plan is to increase the number of users to a group in the next step while the final goal is training at platoon level.

For each client in the current demonstrator the input layer provides position and orientation data from the Inertial Measurement Unit (IMU) of an HMD with an attached camera for inside-out marker tracking as well as from a motion capture suit. The plugin-layer integrates the devices with the Immersive Deck, which in turn fuses the tracking data. These technologies provide the basis for an immersive and interactive user experience of the environment.

In addition, the plugin-layer integrates an RFID reader, which supplies information about the proximity of RFID-tagged objects. Furthermore, a button on the chest of the user provides options for discrete input. Finally, each user is equipped with an RGB-D sensor, which provides a colour and depth image stream for reconstruction of real objects in the VE. The system visualizes real objects, which are within two meters of the camera, so an individual user can see his/her entire own body and close objects/users. In order to track equipment items we equipped them with RFID-tags and the users with an RFID-reader on the dominant lower-arm. Once a user grabs such an object, the RFID-reader discovers the tag and the application layer updates the state of the object to be attached to a certain user's hand. In combination with tracking data from the motion capture suit, the system can determine the position of the object in world space to within an accuracy of about 25cm. In the multi-user environment other users can then see a corresponding virtual object rendered at the interacting user's hand position. In addition, we apply the rotation of the user's hand to the object so it is rotated in the approximately correct way and observers in a multi-user scenario can more easily interpret the action. The drawback of this approach is that virtual items have to be predefined beforehand, resulting in a decrease of flexibility compared to the RGB-D sensor based approach.

Furthermore, the multi-user management distributes the users' head poses and motion capture data, which is visualized by means of avatars. Therefore, not only can users visually follow the actions of others, but also they can communicate non-verbally by gestures, with a great benefit for collaborative scenarios.

Finally, in the current demonstrator we render video and audio output on a VR HMD.

In the next step the prototype will also provide integration of an AR HMD and gesture interaction targeting requirements of a command and control system. Furthermore, a mobile robot platform will be integrated for haptic feedback to increase realism and immersion of the simulation.

4.2 Server

The server part of the application layer contains a number of modules and interfaces providing functionalities to generate and manage the training simulation. Central element is the user-management and distribution service which is responsible for the multi-user collaboration. All positions and movements are synced with the server and sent to other users by using a multicast connection. Every client renders the movements of all participants and offers the possibility to trace their gestures and communicate visually. Furthermore, the usage of the gamepad eliminates the physical space restriction by offering a way to move around within the complete large-scale VE by a virtual vehicle without leaving their physical real world location. An accelerated navigation mechanism is used to distribute the translation data fast enough to accomplish a fluent simulation, which is critical for fast movements. Furthermore, the server provides multiple after action review (AAR) functionalities, to analyse, monitor and supervise the training process. The mentioned VE is managed and controlled by the server with a basic control UI, to give an operator the ability to maintain all actions and execute control different tasks.

Our concept also plans integration of various subsystems, mainly 3D GIS, "ABC-Informationssystem" and a

separate planning and monitoring module. The latter will integrate with existing AAR methods and in addition allow creation and adaptation of training environments. Terrain data from a 3D GIS system will be integrated in the planning module, while real-time position data will be used in the future command and control system. Furthermore, integration with the “ABC-Informationssystem” will provide realistic data of CBRN contamination. Finally, integration of environmental sensors will allow realistic updates and predictions of contamination spreads and other environmental effects.

5.0 IMPLEMENTATION

The implementation of our current demonstrator system integrates a number of hard- and software components.

5.1 Hardware

The computational platform on the client side of our system (shown in Figure 2) is a mobile VR backpack PC, the Schenker XMG Walker with an Intel Core i7-6700HQ, a NVIDIA GeForce GTX 1070 8GB GDDR5 and 32GB of RAM running Windows 10. Furthermore, we use an Oculus Rift CV1 fully immersive HMD for visualization and audio output. Our system utilizes the IMU of the HMD together with a marker tracking solution running on monochrome images from an IDS uEye IDS camera uEye UI-3251LE (please refer to [26] for details on the tracking system). For the RGB-D sensor required in AV we are employing an Intel Realsense SR300 with a depth resolution of 640x480 pixel at 60fps and a RGB resolution of up to 1920x1080 pixel at 30fps. Both imaging devices attach to the HMD by a 3D-printed custom-designed clamp. Furthermore, the Perception Neuron motion capture system records users' arm and leg movements. In addition, the UHF-RFID reader Sparkfun M6E Nano provides input on proximity of tags.

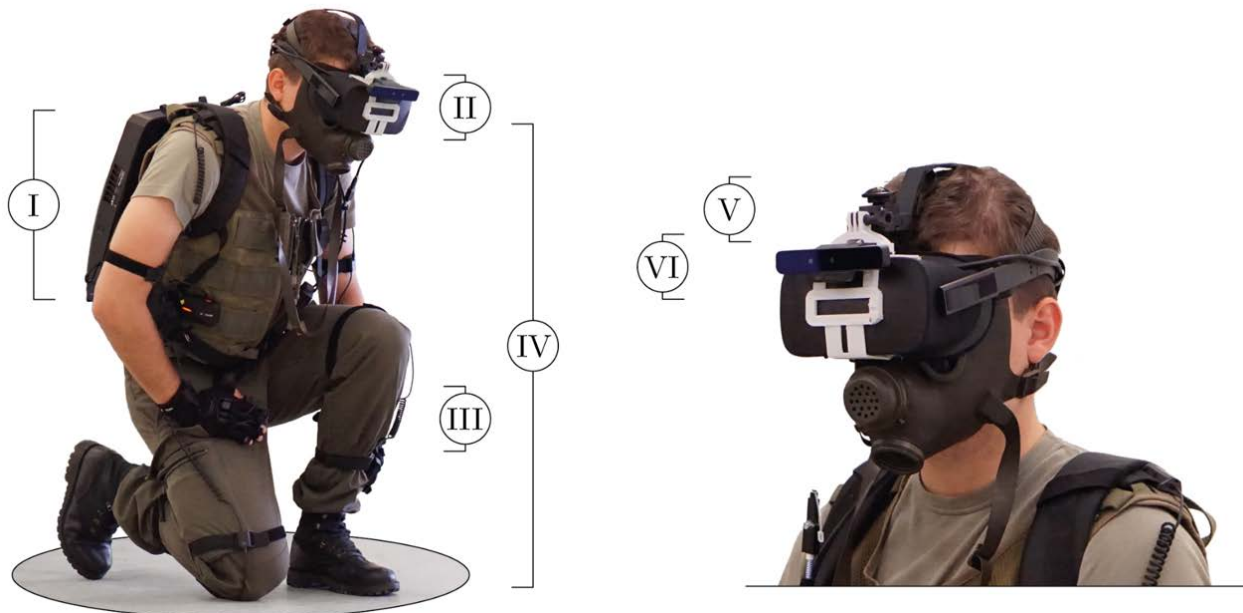


Figure 2: User wearing the setup with: I VR Backpack, II HMD, III RFID-reader, IV MoCap suit, V/VI tracking/RGB-D camera.

Finally, we use a push button and contact block of the RAFIX 30 FS + system wired to a NodeMCU development board. Fixed to the chest of the user in a customized 3D-printed enclosure (as seen in Figure 7)

button presses bring up and select menu items in VR. In our current prototype all input devices are connected via USB cables to the backpack PC. The clients connect wirelessly to the server through Wi-Fi operating in the 5 GHz band. Therefore, each client-setup is independent and mobile within the Wi-Fi range.

The server runs on a PC with an Intel i7-7700 processor, 8GB RAM and an NVIDIA GeForce GTX 1060 graphics card. Due to the desktop setup the computational load is less demanding on the server side. Besides traditional mouse and keyboard input a Microsoft XBOX One controller is connected to the server for use in vehicle navigation.

5.2 Software

5.2.1 Framework

The software builds upon an updated version of the Immersive Deck framework as first described in [26] running Unity3D 2017.2.0f3 game engine [27]. Immersive Deck provides several functionalities enhancing development of a multi-user VR application. The basic configuration is a client-server setup, where multiple VR-clients connect to one desktop-server.

5.2.2 Application Scenarios

Our demonstrator implements a CBRN defence Recce based on the requirements summarized in subsection 3.1 and in close collaboration with specialists of the AAF. For this scenario, we created a virtual environment of 10x10km with a 2500m airspace, which is not yet the size that we plan for the final system. It is modelled after a real rural area located in northern Austria. The area includes a village with residential, administrative, commercial and industrial buildings (see Figure 3) and infrastructure like streets and is suited for training a motorized squad, although the focus of this work is interaction and collaboration in a dismounted CBRN operation in an area of approximately 15x15m. The major mission tasks in this scenario are observation and detection.



Figure 3: Screenshot of the training environment, showing a village modelled after a real environment.

An operator can configure the scenario regarding the simulated hazard materials - i.e. chemical agents in various physical states - the weather conditions and time of day. Users are able to move within the entire area by natural walking and a virtual vehicle (Pinzgauer 710FM), which can bridge larger distances.



Figure 4: Vehicle (Pinzgauer 710FM) for navigation within the training environment (left). Avatar of a soldier operating the ECAM (right).

The CBRN squad staff can wear their actual defence protection suites and additional equipment and radio sets, if required. For the observation task we implemented a binocular (zoom) feature, as-well-as a compass and height angle protractor. The development of virtual contamination scales enhances the detection task. While most devices themselves are integrated via our MR approach, displaying data flexibly and consistent with the VR simulation would be a challenge. Thus custom HUD elements show the information in a similar fashion as on the display of the device. Figure 4 shows a CBRN specialist holding an Enhanced Chemical Agent Monitor (ECAM) in our application.

5.2.3 Operator Interface

The operator interface provides a central UI to control various server functionalities and modules as illustrated in Figure 5. We separated the main window visually into six regions, where every part has its own functionalities. Some include interactive elements and others are only capable of monitoring the scene while the rest offers additional information about the training simulation, e.g. the minimap (III) or the timer (VI). The visual appearance combines several grey shades and a turquoise highlight colour. Therefore, the focus stays on the important elements and points out their actions. The UI for the operator has to offer multiple functions that are stated in the section 3 on the requirements. The main viewport uses the largest amount of space (I). It offers the possibility to supervise the sequence within the three dimensional scene. The operator chooses a camera view on the right side (II), which is expanded afterwards into the main window. We implemented four different perspectives to choose from, which include a free moving camera controlled by mouse and keyboard input, one that is attached to the virtual vehicle, though it is able to look around freely, one for every individual with its first-person perspective and a stationary one that users can place inside the VE. Four cameras of the last type are available to be positioned and the operator can switch between them with the numbered buttons at the bottom of the scene view (I). All virtual cameras, except those of the participants, are controlled with mouse and keyboard input. The user is able to drag the view in every direction and move the position with the WASD-keys, which results in an easy to use and adaptable point of

view over the entire scene. The fluent switch between these aspects offer an instructor many options, to configure his monitoring interface as suitably as possible. Another part of the graphical interface is a minimap (III) (see Figure 5), which is located inside the main view. Figure 6 illustrates the details of this component that shows a map of the terrain from above. Users are able to adjust zoom or extend it to the complete main window with buttons located on the left (I). Besides illustrating the position of the vehicle (III) the predefined area of incidents is marked with a dotted texture (II) and the contaminated region is coloured in turquoise (V). All elements are arranged accordingly around the current active camera (IV). Various interactive elements give an operator the ability to manipulate and interact with a training sequence (see Figure 5 (IV)). Starting from the left upper corner, the first button toggles the visibility of the minimap, while the second one is responsible for the symbols within the map, as for example the vehicle. The event and the contamination buttons toggle the visualizations of the event/contamination areas in the minimap as well as in the 3D scene. In addition, the operator can reduce the user's range of sight, by turning on a particle based rain visualization. Furthermore, a translation switch activates the ability to move the selected camera with the keyboard. Additionally, the operator can unlock a predefined series of explosions, which can be released with the explosion button. Finally, the last button enables a debug window (see Figure 5 (V)), which provides information and error messages concerning the state of the simulation.

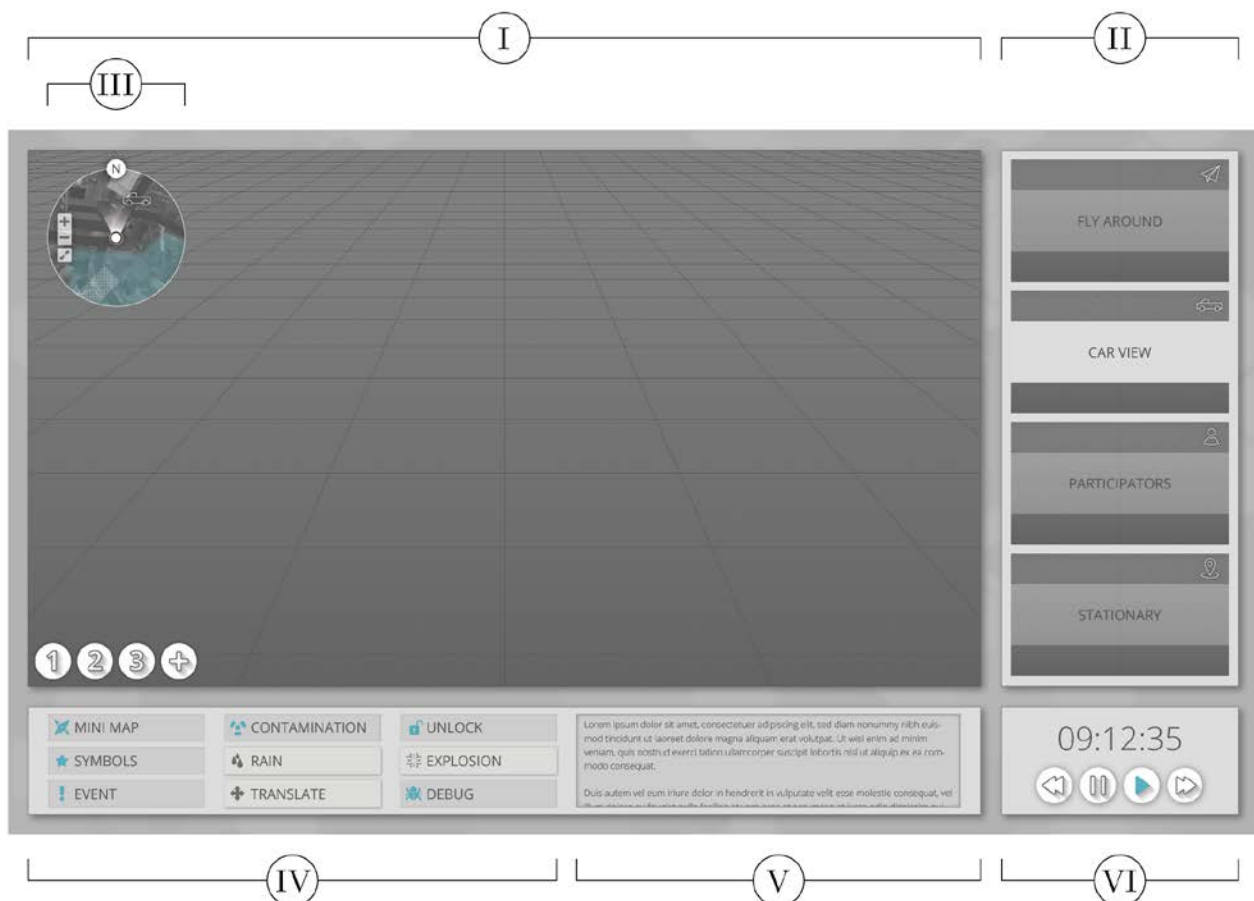


Figure 5: The operator UI with different functional regions including the main scene view (I), four different camera perspective settings (II), a minimap (III), function keys (IV), a debug output window (V) and a time control and recording panel (VI)

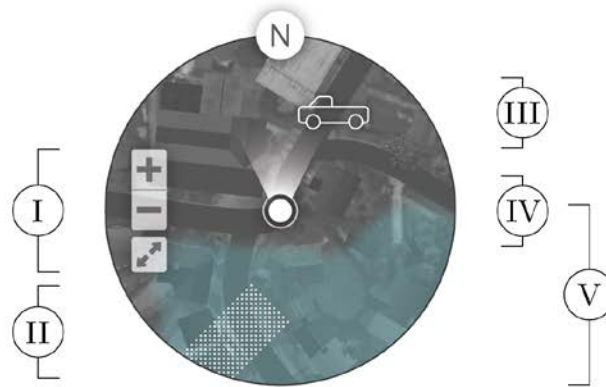


Figure 6: The minimap including zoom tools (I), the location of the incidents (II), the virtual vehicle (III), the position and rotation of the current selected camera aspect (IV) and the region of contamination (V).

Finally, a time control and recording panel (VI) provides capabilities for AAR. It allows timing of the simulation and recording of videos from training sessions. All described functionalities offer various capabilities to monitor training sequences and trigger events within the simulation. In this highly adaptable interface, operators can utilize those features that suit best for their needs.

5.2.4 Large Virtual World Generation

To provide realism in the simulation, an area with approximately ten by ten kilometers in Northeastern Austria was selected to be transferred into our VE. We use satellite images from Google Maps [28] in our demonstrator. The images have a total resolution of 10240 to 10240 pixel. Each pixel represents one square meter in reality and before importing them into Unity3D, the image is divided into 25 tiles with dimensions of 2048 to 2048 pixels, as this is the maximum the engine can handle on terrains. To give the terrain its height profile, we used a digital ground model from data.gv.at [29] with a grid of ten by ten meters, which is converted with QGIS [30] into a 16bit greyscale raw image. The raster images stores surface elevation data, which is converted by Unity3D into terrain meshes. The imported heightmap does have a lower pixel density and therefore steps occur on the terrain. A smoothing tool removes them and the plugin TerrainStitcher [31] merges all tiles into one big mesh without gaps. The Unity3D plugins Gaia [32] and EasyRoads3D [33], add world elements such as trees, houses, grass, and streets.

5.2.5 Multi-User Interaction

The server manages connections to multiple clients and allows customization of the clients' avatars through a customized GUI. Properties like player height can be calibrated in this GUI. Besides distribution of avatars' and objects' poses the server controls the ownership of objects equipped with RFID-tags. Once an RFID-reader detects a tag, the corresponding client sends a call to the server, which in turn attaches the object to the user's hand and notifies all clients to do the same. Similar to its avatar the client assumes control of the object and the movement originating in the client's motion capture suit is synchronized over the server to all clients. In this way multiple users can train together as shown in Figure 7. We built our current system for a squad of max. four people, however it could be extended to more, limited mainly by aspects like network bandwidth and server performance.

5.2.6 Augmented Virtuality

We integrated the Intel Realsense SR300 by accessing the Software Development Kit (SDK) 2016 R3 from Intel [34] from the plugin layer in our system. The SDK offers functions to start streaming frames, extracting

pixel values and many more. The plugin opens a stream and provides RGB and depth data as color (1280x720) respectively monochrome (640x480) image data. We transform both into a Unity3D texture and use a mesh with 14400 vertices as basic geometry. To texture the mesh properly the RGB and depth images are aligned, filtered and the vertex positions of the meshes set according to depths in a strongly optimized process. Through the texture's alpha value we continually fade out pixel, that are too far for near range augmented virtuality or too close to the sensor's minimum operation distance.

6.0 EVALUATION

We conducted a user study with early versions of the system with 13 participants, from the National Defence Academy and Competence Center NBC Defence of the Austrian armed forces. Figure 7 shows four users in our VR training system at the Competence Center NBC Defence.

The emphasis in this evaluation was placed on navigation, interaction with virtual equipment, collaborative training with multiple users, training environment, trainer evaluation and education in CBRN defence. In addition, we collected data on interaction with real objects in a mixed reality setting.

6.1 Demography

Thirteen participants were involved in the experiment (12 male, 1 female), with an age between 19 and 51 years ($\mu = 34$, $\sigma = 12$). All participants are experts in the field of CBRN defence from the National Defence Academy and the Competence Center NBC Defence of the Austrian armed forces. All but two occupy leading positions and all are associated with training and education activities. Only a small number of experts with this kind of qualification exists on a national as well as an international level and volunteers are therefore very hard to find. Seven participants reported previous experience with VR. All participants considered themselves to be average or moderately fit.

6.2 Methodology

We evaluated early versions of the system at two separate occasions approximately half-a-year apart with six respectively seven participants. We used feedback of the first round to improve certain aspects of the demonstrator for the second. After filling in a short pre-questionnaire, the users could explore the open world and system features freely in groups of two to four people and in their own time. During the test, the experimenters encouraged the participants to try out functionalities or procedures. During one of the occasions six of the participants were asked to also use the operator interface of the system.

After the tests, we asked the participants for their opinion on a number of aspects of the system and the application. We used questionnaires with a five point Likert scale and some open questions.

6.3 Results

The presentation of results in this paper mainly focusses on questions regarding navigation, interaction with virtual equipment, collaborative training with multiple users, training environment, trainer evaluation and education in CBRN defence. The results of interaction with real objects in a mixed reality setting are not discussed here, because it would be beyond the scope of this publication.



Figure 7: Users during multi-user CBRN recce training, wearing protective masks and VR equipment.

6.3.1 Evaluation of the Trainee Perspective

Our system provides two modes of navigation within the virtual environment. The first is navigation in a virtual vehicle, which one of the users can control by gamepad. The second is navigation by walking. We have evaluated both modes separately according to difficulty, speed and users' preference.

Navigation with the gamepad was rated simple or very simple by most users ($\mu = 4.18, \sigma = 0.75$). Most of the users had already at least some experience in the use of gamepads ($\mu = 3.39, \sigma = 1.26$). However, no correlation between prior experience and ease of use in our VR simulation could be established. The speed of navigation with the gamepad and virtual vehicle was rated little above average ($\mu = 3.18, \sigma = 1.25$). This might be attributed to the fact, that we set the maximum speed of the virtual vehicle to about half of the real vehicle's approximately 100km/h in order to avoid cyber-sickness. However, improvements of synchronization of vehicle movement in the current version of the demonstrator should allow for higher speeds. Finally, about half the users at least somewhat liked the navigation method ($\mu = 3.71, \sigma = 0.95$), again no correlation could be found to prior experience. From the users' written answers and comments we know that control of the virtual vehicle with the gamepad can be challenging in certain situations. Current and future optimizations will target vehicle physics to avoid frustrating situations.

Ten of the participants rated navigation by walking - supported through our wide-area tracking system - as easy or very easy ($\mu = 3.77, \sigma = 0.93$). The speed of navigation was rated above average

($\mu = 3.39, \sigma = 1.33$), although with significant deviations among the users. Overall, the navigation method was liked or liked very much by most users ($\mu = 3.64, \sigma = 1.12$).

We evaluated a number of virtual equipment options (compass, height protractor, binoculars, enhanced chemical agent monitor) during the second evaluation-round with six participants. Interaction with the menu itself was rated mostly positive ($\mu = 3.67, \sigma = 1.21$, respectively $\mu = 4.0, \sigma = 1.0$ when only considering participants with normal vision). However, inaccuracies in tracking, especially in border-regions of the tracking area, made it more difficult for some users to select menu items by coordinated button presses and head-rotations, which might account for the large variance of the responses. Interaction with the compass was considered easy or very easy by all participants ($\mu = 4.33, \sigma = 0.52$). Difficulty of using the height protractor was answered similarly well ($\mu = 4.4, \sigma = 0.89$). Handling of the binoculars has been rated slightly more difficult ($\mu = 3.5, \sigma = 1.64$, respectively $\mu = 4.0, \sigma = 1.22$ when only considering participants with normal vision). Especially feedback of one participant suggests different placement of the visualization. This is also true for visualization of readings of the enhanced chemical agent monitor, which especially while wearing a protection mask resulted in bad visibility at the users' periphery and only average ratings for ease of use ($\mu = 3.0, \sigma = 1.23$).

Please refer to Figure 8 for an illustration of some of these results.

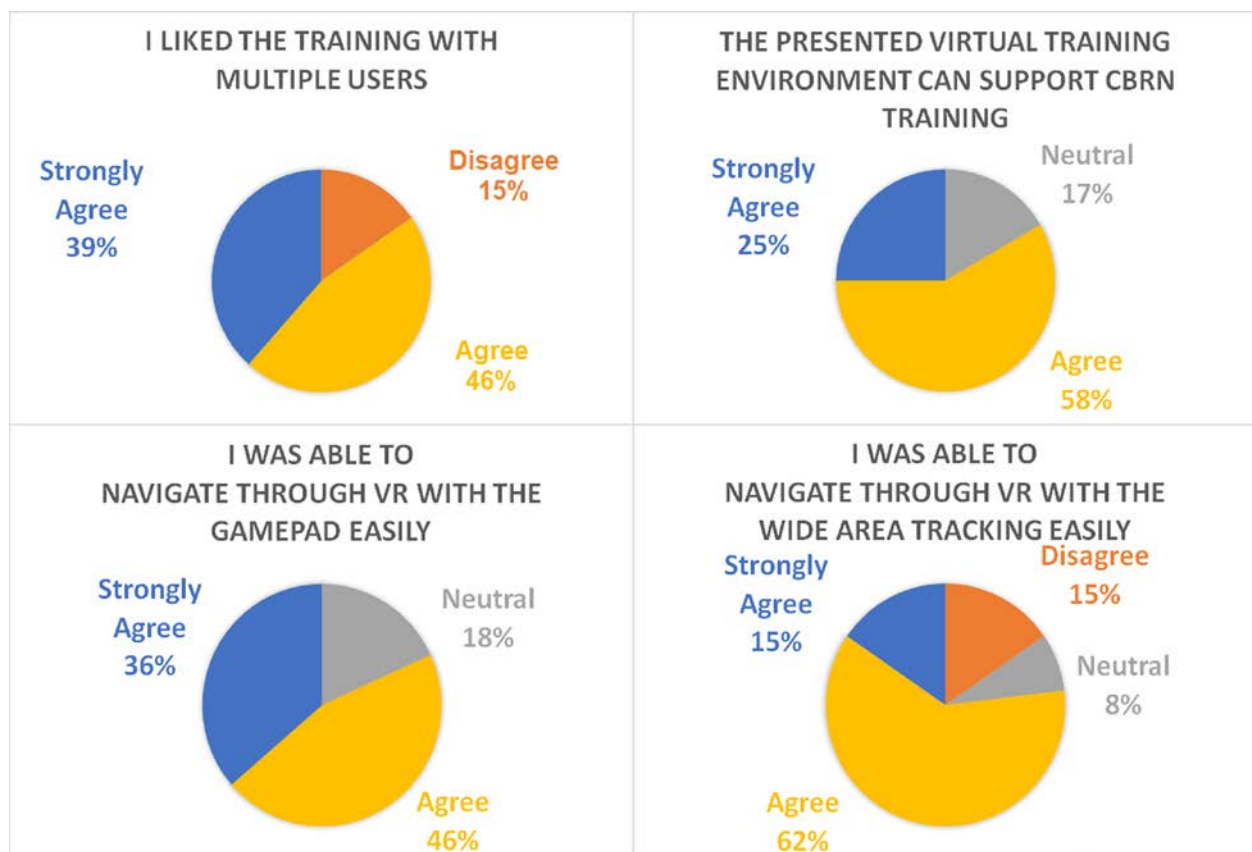


Figure 8: Results from the questionnaires regarding VR CBRN training.

We asked a number of questions regarding the quality of the virtual training environment and usability of the VR equipment. Most of the users felt a strong immersion into the virtual world ($\mu = 3.85, \sigma = 0.8$). Even more, our expert users agreed that the virtual training environment presented in the demonstrator can support CBRN training ($\mu = 4.08, \sigma = 0.67$). Participants in average rated the suitability of the simulation's visual

quality as good for an observation task ($\mu = 3.92, \sigma = 0.86$) and sufficient to good for a detection task ($\mu = 3.62, \sigma = 0.96$). The results regarding the visual quality of various objects and elements of the simulation was rated similarly for the terrain ($\mu = 3.92, \sigma = 0.86$), the vegetation ($\mu = 3.62, \sigma = 0.87$), buildings ($\mu = 3.85, \sigma = 0.80$), roads and pathways ($\mu = 3.5, \sigma = 1.0$) and events ($\mu = 3.67, \sigma = 0.78$). Only the avatar just received an average rating of ($\mu = 2.92, \sigma = 1.38$).

The participants agreed very much on the importance of being able to train with multiple users ($\mu = 4.92, \sigma = 0.28$) in the application scenario. In general, users liked training with others in the system ($\mu = 4.08, \sigma = 1.04$). They were able to communicate with their partners ($\mu = 3.42, \sigma = 1.24$) and could also follow the actions of their training partners ($\mu = 3.83, \sigma = 0.58$).

The overall ratings for statements above regarding collaboration and avatar dropped mainly due to calibration issues with some of the inertial motion capture suits (users complained in the free comments about twisted or disappearing avatars). This explains also the outliers regarding the first multi-user questions illustrated in Figure 8. Considering only users where the calibration worked properly, the values are better by around a half point.

Finally, we asked our last seven participants if the VR equipment was comfortable and easy to wear, which was much agreed on ($\mu = 4.14, \sigma = 0.69$), while comfort and ease of use degraded significantly, when combined with CBRN protection equipment ($\mu = 2.75, \sigma = 1.26$).

In the end, eleven of the participants agreed “much” or “very much” that the presented system can be used to support training for CBRN-crisis preparedness. One user considered it “very interesting as complementary training”.

6.3.1 Evaluation of the Trainer Perspective

During the user-study we gave six of the participants the chance to use the system from the operator side through the monitoring and controlling interface described in subsection 5.3.2. This subsection presents results from the post-questionnaire. The participants found it very easy to observe the simulation and retrace the participants movements and the whole training sequence ($\mu = 4.5, \sigma = 0.76$). The functionality to interfere and trigger incidents within the simulation received even better feedback ($\mu = 4.67, \sigma = 0.47$).

These two statements point out that our developed control interface offers a good way to supervise and monitor all procedures. Furthermore, users found the handling of the interface appealing in general ($\mu = 4.33, \sigma = 0.47$).

A number of statements regarding the usability of the operator interface were presented to the users. The complexity of the UI was rated very low with a mean value of $\mu = 1.5$ and a standard deviation of $\sigma = 0.50$. Usage of the interface on the other side was rated very simple ($\mu = 4.33, \sigma = 0.75$). Five out of the six participants agreed that no technical experienced personnel would be necessary for assistance during a training sequence. Consequently, we could conclude that almost all of them are confident with using the system by themselves as all functionalities and actions are properly mapped onto the UI for an intuitive operation. This is also supported by agreement to the next statement about good integration of the different functionalities in the interface ($\mu = 4.67, \sigma = 0.47$).

All participants agreed much or very much ($\mu = 4.50, \sigma = 0.50$) that also other people would learn using the interface quickly and most of them are sure that they handled the GUI correctly ($\mu = 4.33, \sigma = 0.47$) without having to learn a lot of things.

All participants agreed “much” or “very much” that the operator interface can support training in CBRN defence ($\mu = 4.67, \sigma = 0.47$). Furthermore, we asked the participants to rate and rank the three features

“Monitoring of training sequences”, “Ability to switch camera perspectives” and “Ability to position incidents”. Although the three aspects received the same average rating of 4.67 “Monitoring of training sequences” and “Ability to position incidents” each was ranked first by half of the users.

Participants declared their positive and negative experiences with the operator interface in an open questions section. Multiple statements in the open questions deal with a debriefing, to be more precise, capture camera outputs for analysing all occurrences and actions during the simulation. These features of an AAR are already implemented in the current version of the demonstrator, while the request for contaminations moving downwind will be implemented in the future prototype.

6.4 Discussion

From the results we can see that the proposed multi-user VR system is highly relevant for the use-case. Participants found it relatively easy to navigate within the training environment by gamepad and natural walking. However, we observed relatively large variations in perceived interaction speed and preference for both navigation methods. One reason for this might lie in the differences how participants were coping with imperfections in tracking quality, a property that is continually improving in current and future implementations.

Difficulty of using the various virtual equipment items was rated between average and very simple. Especially using a cursor and running scale for compass and height protractor in the implemented form therefore appears to be a good solution in the proposed context. Others were easy to improve by small adaptations of the UI items following user input, such as the readings of the enhanced chemical agent monitor. Some features, such as the menu item selection itself, will be improved through updated versions of the tracking system, as stated above.

The quality of the virtual training environment and different virtual objects was largely rated as well suited for the various tasks. Nevertheless, there is room for improvement in the visual quality of certain elements such as roads and vegetation. However, there is always a trade-off between performance and visual quality. Additionally, tracking as-well-as other back-ground tasks of our VR-system limit the available resources further. Especially in combination with the vast virtual environment we had to reduce geometric detail and texture resolution in several cases to achieve frame rates suitable for VR. Future system configurations with more CPU- and GPU-performance, however, could alleviate these restrictions.

Furthermore, the level of detail is usually limited, when using freely available aerial images that can be used to texture terrain. The same is true for freely or cheaply available 3D models. Therefore, visual quality is also a cost factor, even more so with the time- and cost-effort when modelling customized content.

Multi-user training and collaboration is a corner stone of the proposed application area, which was confirmed by the experts in our questionnaires. Feedback regarding these aspects was largely positive, despite some technical issues. Fast, reliable and secure distribution of data, especially between many users, is challenging and will be a critical aspect on group and platoon level.

Two participants of our user-study had corrected vision, but could not wear their glasses with the HMD. Therefore, in certain situations of the training they had problems with the visual perception of the environment, e.g. properly seeing their training partners' actions. In the future, corrective lenses incorporated in the HMD could provide an improvement for users with vision aid. Unfortunately, currently not many HMD manufacturers offer this feature. Nevertheless, collaboration in a multi-user scenario was possible and very much appreciated by the users. Furthermore, our novel system makes it possible to follow other user's interactions with equipment items.

The equipment necessary for the VR system alone was considered comfortable to wear, while the

combination with CBRN equipment was rated significantly less comfortable. We did not ask the participants for their opinion on the CBRN equipment alone in the questionnaires, but from discussions following the study, we conclude that discomfort largely results from the protection mask itself rather than the combination.

The results from the evaluation of the operator interface show very encouraging results. The design of the interface hides unnecessary complexities from the operator and exposes only relevant core-functionalities. Responses of our expert users rated the interface easy to use and easy to learn. In the long term, the fact that most participants would consider technical assistance during operation unnecessary is very important for cost-efficient operation. Although we have not evaluated the AAR capabilities of the operator interface yet, we are very optimistic regarding future user-studies, since they follow the same design paradigms as the rest of the interface and incorporate a lot of feedback from our expert users.

7.0 CONCLUSION & FUTURE WORK

We have presented how we transferred requirements of CBRN training into the implementation of a demonstrator providing an immersive multi-user VR training environment. Besides the requirements, we showed a visionary design concept and described in detail how we implemented parts of this concept into a working demonstrator. The demonstrator provides a large number of features including navigation, interaction with virtual and real equipment, collaborative training with multiple users, wide-area training environment, trainer evaluation and education in CBRN defence.

Furthermore, we implemented one of three scenarios offering training possibilities in a CBRN defence recce, which would require massive effort when simulated in reality. Multiple experts from the AAF evaluated an early demonstrator and qualitative and quantitative results show a high acceptance and potential of the system. Most of the system's features showed to be easy to use and more than adequate for the purpose. Due to the early stage of the demonstrator during evaluation, smaller technical issues reduced usability of some aspects, but overall feedback was very positive, suggesting that the system can be used to support training for CBRN-crisis preparedness.

In future work we plan to extend the current demonstrator to a more powerful prototype including all features presented in the system design. This includes extensions towards MR, with integration of an AR HMD and gesture interaction targeting requirements of a command and control system. Furthermore, a mobile robot platform will be integrated for haptic feedback to increase realism and immersion of the simulation. In addition, we plan on the integration of various subsystems, mainly 3D GIS, “ABC-Informationssystem” and a separate planning and monitoring module. The latter will integrate with existing AAR methods and additionally allows creation and adaptation of training environments. The final system will be able to generate a broad range of scenarios and configurations, providing the means of also simulating training situations, which are too expensive or dangerous to create in the real world. Furthermore, integration with the “ABC-Informationssystem” will provide realistic data of CBRN contamination. Finally, integration of environmental sensors will allow realistic updates and predictions of contamination spreads and other environmental effects. Future prototypes will emphasize multi-user training with group and platoon size at a higher technical readiness level, benefitting also from new and improved technologies (e.g. motion capture suits, tracking etc.). We plan to continue the project with Austrian and international partners and funds from Austria's FORTE defence research program and more long term with funding from the European Defence Agency.

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Joint Simulation Environment for United States Air Force Test Support

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ABSTRACT

Advances in integrated, multi-domain warfighting capabilities are challenging the ability of militaries to rapidly design, develop, field, support, test, and train next generation war fighting capabilities. Today's physical test ranges, in their present form, are inadequate to meet the testing and training needs of these future integrated weapon systems. Future test capabilities must be augmented with state-of-the-art modelling and simulation technologies to form a virtual range capable of meeting development, test, and training needs in a rapid and cost-effective manner. The United States Air Force, in concert with our Service partners, intends to develop an integrated modelling and simulation based virtual test range to address these challenges. The Joint Simulation Environment (JSE) leverages lessons learned from recent modelling and simulation activities in support of Joint Air Force and Navy testing. JSE seeks to advance the state of the art in modelling and simulation technologies applied to test, training, and experimentation. This paper will discuss JSE use in supporting Air Force objectives, challenges, way-forward, and potential NATO Partnership opportunities.

1.0 INTRODUCTION

The overall vision for the Air Force for the JSE capability is to improve developmental and operational test quality and efficiency, provide a stable and secure environment for cross-platform advanced training and tactics development, and better inform future acquisition decisions by improving the quality of integrated force analysis of alternative studies via multiple fidelity level experimentation and capability demonstration. Specific JSE objectives include:

- (1) A government-owned, multi-platform advanced M&S capability that overcomes existing open-air range limitations, to include system availability, threat density, and safety and security concerns.
- (2) An open architecture that enables composability and integration of models and simulations of varying levels of fidelity, to include blue and red aircraft operators-in-the-loop, threats, weapons, terrain and weather.
- (3) Interoperability with other services and foreign partners within the JSE and extension to other required simulation environments.
- (4) Opportunity for international testing and training/experimentation.

The overall goal of JSE is to enable smarter, faster acquisition by providing data in order to enable war fighter and acquisition decision makers to make risk-informed decisions in support of the recently published U.S. National Defense Strategy. *Dr. Eileen A. Bjorkman, Deputy Director of Test and Evaluation*

Air Force leadership recognized the need to provide a credible test environment to support current and future system testing, not currently possible on current test ranges due to a number of limiting factors. These factors include geographical constraints, technology limitations, electronic warfare limitations, frequency spectrum interference, operational limitations, and safety concerns. Reviewing these factors is instructive since they form or significantly contribute to the requirements foundation of the JSE for the Air Force.

2.0 JSE REQUIREMENTS

In 2017, the Chief of Staff of the Air Force (CSAF) directed the AF community to pursue a synthetic test capability designed to address current and future test and training deficiencies. The funding for this effort, provided by the AF to support the development activities and a lead execution organization (412th TW at Edwards AFB) within the test community, was established starting in Fiscal Year 2019. The Air Force Test and Evaluation Office (AF/TE) directed the team to develop and field a synthetic test capability by FY23 at both Edwards and Nellis AFBs. This effort links with the development of the synthetic test environment currently in development at Patuxent River NAS using a joint USN, USAF, and Intelligence Agency team.

The requirements development effort addresses three primary areas: (1) test limitations within today's physical test ranges, (2) anticipation of future capabilities and associated needs, and (3) balancing of cost and risk in achieving a useable and flexible design that can readily grow in time.

2.1 Limitations on today's test ranges

- Geographical constraints affect the ability of the live assets to properly set up the engagement, employ longer-range weapons, maneuver, or employ CONOPS/TTPs within larger mission fleets/forces against an air or ground threat system or integrated air defense system (IADS).
- Technology limitations limit the integration of live assets with modelling and simulation entities in the execution of test objectives. While the Test community has utilized synthetic environments for numerous years on the test ranges to augment a live force, significant technology-based obstacles exist that limit the effectiveness of the synthetic environment, such as the inability to replicate a dense threat environment employing complex signals in real time.
- Electronic Warfare Limitations include the replication of dense and complex electronic warfare environments in real time within a digital format. Achieving this computationally challenging environment through the use of complex fully digital signals would allow the simulation world to rapidly and cost-effectively scale the environment and be more representative of today's battlespace.
- Frequency Spectrum Interference limits today's test ranges in the type, and strength of electronic signals permissible on the range. This may include not only electronic warfare signals, but also IFF and RF communications that are not bound to range physical characteristics and may be adjacent to commercial frequency spectrums causing unintended electromagnetic spill over.
- Operational Limitations prevent the full range of possible engagements within a Mission Effects or Kill Chain. The most obvious limitation is the safety-driven limitation of the use of live weapons in close proximity to manned systems to complete the Kill Chain or engagement on a test range.
- Safety Concerns address not only the inability to utilize weapons, but also complex engagements of multiple aircraft aggressively manoeuvring in a confined airspace and with terrain considerations. Range safety is a primary concern when testing aircraft and routinely provide test limitations that can adversely affect test results.

The JSE seeks to remove or limit these constraints by developing a virtual test range to augment the existing physical ranges when testing systems or system of systems.

2.2 Anticipation of future system test needs

Next generation testing will encompass not only advanced systems and weaponry, but also the need for systems to work in close coordination (between US and NATO partners) within an information-based system of systems. Information technologies will provide broadband, high-speed connectivity that will enable shared information-based applications to support improved detection, tracking, identification, and weapon delivery solutions. A future synthetic test range may be the only viable means to test a future information-

based system/system-of-system kill chain. Viability implies not only the ability to test the technologies, but to do so in a cost-effective, risk-mitigated, and complete (full kill chain) manner. Future test needs may include:

- **Battlespace Density/Complexity:** The synthetic range must be able to produce large numbers of assets of varying complexity to properly “feed” the System-Under-Test (SUT) in a credible battlespace environment to support the necessary and appropriate test conditions. These feeds are a combination of virtual and constructive entities from a variety of simulation capabilities in a distributed environment.
- **Geo-Specific Place/Time Testing:** The synthetic range must be able to replicate geo-specific terrain on any test range or in any area of the world. This capability must include not only the support of non-imaged sensors, but also image-based sensors including cultural features and threats/targets-of-interest to the test community. An additional requirement is to replicate this geo-specific place within varying time spans from current year to any number of future projected years.
- **Representation of Future Rapid and Adaptive Threat Capabilities:** The synthetic range must be able to produce a realistic representation of future threats and the resulting interaction with the System Under Test (SUT). Stapleton observed that we do not realistically represent technologies within our tests often substituting current technologies in place of future technologies that are not well understood, or similarly, future effects that are not well understood. This pattern is often repeated with regard to our future threat representations, resulting in unrealistic own and opposing forces pairings under unrealistic engagement conditions. As more systems increasingly rely upon easily upgradable software this trend becomes more pervasive in our testing. [1]
- **Multi-Domain Integration:** The synthetic range must be able to produce the ability to test the kill chain across multiple domains including air, space, sea, land, and cyber. The synthetic test range must address the multi-domain aspects of future systems and their associated war fighting capabilities. Additionally, the nature of a multi-domain, multi-national, complex array of sensors distributed across the air, space, and cyber domains presents a daunting test challenge. New approaches and methodologies are required to address the complexity challenge such as those suggested by Sheard. [2]
- **Future Kill Chain:** The synthetic range must be able to produce the ability to test the kill chain from detection (on-board or off-board ISR sources) through tracking, through identification (ID), to targeting, and through Battle Damage Assessment (BDA). Enabling a cross discipline kill chain involves moving from air/space/sea/land/cyber target detection via advanced sensors, data processing, data mining, networking, cueing, track formation and sustainment, track correlation, track fusion including ID from diverse information sources, rapid decision-making with support from automation, and Artificial Intelligence. While it is possible to deconstruct a test into sub-objectives, the entire kill chain must be testable within a synthetic range.
- **Collaboration:** A future kill chain may elect to combine steps within today’s kill chain reducing the need to share the information across network spaces or it may elect to enable many spectrally diverse sensors located on various platforms and in effect expand the kill chain collaboration. This collapse and expansion might occur dynamically during the prosecution of a mission and be accelerated by automation. Support platforms/sensors or nodes owned by US or US Partners (NATO) must work in collaboration within this dynamic battlespace. Additionally, US/US Partners must communicate and dynamically and rapidly share raw and/or processed information. The Command and Control (C2) aspects of a future fight will require a higher degree of decision-making collaboration that must keep pace with a highly dynamic and time constrained modern battlespace while addressing collaboration barriers (such as language). A synthetic range must be able to support the testing of these challenges from providing credible sensor modelling, to connectivity, to addressing rapid and dynamic decision-making requirements.

- **Automation:** Future warfighting systems will continue to see improved automation requiring test capabilities to support various levels of autonomy from pilot assisted autonomy to complete machine-to-machine autonomy requiring no human intervention. These varying levels of automation located throughout the kill chain provide significant challenges to the tester with or without a synthetic test range.
- **Geo-Specific Weather:** While a physical range cannot control the weather, a synthetic range can provide dynamic and varying weather conditions within the testing environment. A synthetic range must provide the ability to produce and alter weather conditions within the test environment that correlates non-imaged and imaged sensors, networks, and nodes.
- **Electronic Warfare (EW):** A synthetic range can avoid the EW issues found on physical ranges. The synthetic EW signal is not observable by our enemies (not propagated in physical space), does not infringe on commercial spectrums, and can be readily modifiable as desired. There are four principle challenges for Modelling and Simulation today when employing EW techniques: (1) Generating and propagating signal complexity in real time in a dense EW environment, (2) Scaling EW signals in space, (3) Verification and Validation of the EW signals and their effect within the environment, and (4) properly modelling the Electronic Attack and Electronic Protection interactions given the available fidelity in today's models.
- **Security:** A synthetic range must address security concerns as various programs interoperate within a common operational battlespace. Multi-Level-Security (MLS) concerns are central to the development and operation of the test range. MLS concerns are addressed early in the design and potential solutions will only consider proven and previously approved approaches.

2.3 Balancing Cost and Risk

Achieving a viable synthetic test range design and implementation approach requires the architect to balance available modelling and simulation technologies with development and sustainment cost and risk. The AF budget established cost numbers for the development effort. The AF development team elected to balance the design of the JSE in the following manner:

- **Use of an existing prototype:** The JSE for broad AF use must expand capabilities from an existing environment developed jointly by the Navy and AF to support broad operational testing activities. The Joint Navy, AF, and Intelligence community team constructed this first environment, led by the Navy, at Patuxent River Naval Air Station (NAS) located in Maryland, United States. Using a working prototype allows the team to continue development and the Air Force to leverage these prior investments while mitigating development risk.
- **Limited Development:** The Air Force elected to limit environment development where practical by reusing models/components within the existing environment. The current reuse is over 60% within the environment. Sixty percent (60%) of the models the Air Force intends to use are already developed and in use within the community of interest. Of the remaining development items, 20% are currently in development, with the remaining items scheduled to start development in FY20.
- **The System-Under-Test (SUT)** will generally contain rehosted Operational Flight Program (OFP) code supplied by the appropriate System Program Office. The developing contractor must work with the Government JSE team to integrate the SUT with the JSE environment. These costs and risks are appropriately aligned with the System Program Office and Prime Weapon System Contractor.
- **Development of an Information Broker** that is responsible for the proper message exchanges supporting the necessary timing, scheduling, routing, and other services is critical to ensuring the synthetic test range operates as designed. For the next iteration of the JSE, this Information Broker is known as the Information Exchange Services Matrix (IESM). The IESM is information/domain

agnostic and can be utilized for not only test, but also training and experimentation uses. The IESM is the subject of a separate paper produced by the MITRE Corporation.

- **Distributed Operations:** There is a desire within the test and training community to connect geographically distributed sites, cost-effectively enabling larger and more diverse testing and training including cross-service components. This requirement is not contained within the initial JSE development effort, but the synthetic range design will provide design accommodations to ensure the range can support distributed operations in the near future. This requirement is balancing cost and development risk by early accommodation of distributed operation needs in the design coupled with early prototyping.
- **Blending of Commercial and Government Off-The-Shelf (COTS/GOTS) products while limiting new development to only those critical capabilities without which the JSE cannot succeed:** This risk-managed approach allows JSE to establish an early baseline from which to measure development progress while balancing risk and cost. While the JSE is government-owned, its composable nature allows for the addition of commercial and even proprietary components as required. All solutions must provide specific metadata that provides the needed conceptual and technical transparency of the solution needed to ensure integration into the infrastructure, interoperability of the simulations, and composability of the concepts. [4]
- **Development with the goal of NATO Allies collaborative development and use:** Foundational architecture and software decisions allow the sharing of capability with US allies supporting an objective of collaborative development and use for Test and Training applications. This approach fundamentally changes the technological decisions for the development of the JSE.

Collaboration comes in many forms. The sharing of ideas provides an idea trade space from which to formulate a longer-term collaborative implementation plan. Collaboration can include the cooperative design of common components that provide a foundation for interoperability. In addition, collaboration can result in the joint development of critical components that enable allies to employ operationally relevant CONOPS vis-a-vie integrated or integratable simulation environments.

3.0 JSE ARCHITECTURE APPROACH

The approach selected by the Air Force to utilize and further contribute in developing the synthetic environment begins by defining three regions. Region A is the region where the System-Under-Test (SUT) resides and any other entity or component critical to the testing of the SUT. Entities in Region A have direct interaction with the SUT. Region B entities can have a direct influence on the SUT and may or may not directly interact with the SUT under limited circumstances. Region C entities provide context to the broader scenario and do not directly interact with the SUT.

The idea captured in the development of Regions A, B, and C follows best practices for system engineering. In systems engineering, there is great interest in achieving precise detail in high resolution and fidelity in our system within the system borders (Region A). There are other systems that the SUT has to interact with, but at a lesser fidelity (lesser impact to the SUT performance) (Region B). Finally, there is the context that provides the additional input and may influence our system, but is not influenced by our system (Region C). [3]

REGION A:

- ✓ System Under Test (SUT)
- ✓ Virtual Air Threats (VAT)
- ✓ Lower Fidelity Blue Simulators
- ✓ Weapon Models
- ✓ Common Services required to support the SUT
- ✓ Threat Components
- ✓ Analytic Services

REGION B:

- ✓ "Stand By" Virtual Air Threats (VAT)
- ✓ Lower Fidelity Blue System Models
- ✓ Blue Constructive Entity Generator
- ✓ Threat Constructive Entity Generator

REGION C:

- ✓ Low Fidelity Constructive Air Entities for Battlespace Context

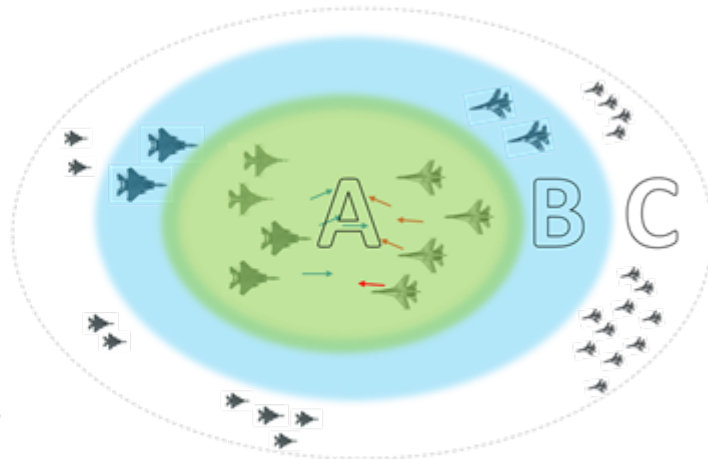


Figure 1: JSE Test Region Description

3.1 Composition of the JSE Architecture

The JSE Architecture approach is to decompose the environment into a limited number of components from which to enable multiple and concurrent development streams. Each component contains a specific suite of requirements necessary to enable select functionality within the environment. The major components will include:

- Representation of own systems in high fidelity
- Representations of opposing systems in high fidelity
- Consistent representation of the environment
- Consistent representation of interactions between these systems in high fidelity
- Representations of own systems in lower fidelity to provide a credible test environment
- Representations of opposing systems in lower fidelity to provide a credible test environment
- Administrative, Infrastructure, Data Collection, Analysis Tools, and other Exercise supporting services

As the JSE designs and implements common services, it would be wise to consider the NATO objectives of interoperable forces. NATO forces must be developed within the collaborative employment and operation in combat theatres. It follows that collaborative test and training is required to meet these objectives. The development of common services includes the development of RF/IR environments, RF-based communication, weapon models/effects, electronic warfare effects, cyber effects, and space models/effects. The intent of the JSE is to allow the end user to alter edge services as required, but to develop an agnostic suite of common services to support a fair fight. JSE is utilizing RF/IR environment services from legacy system software, upgrading the code structure and modelling language to meet today's standards. The US Air Force has developed numerous higher fidelity communication models that will form the basis of the common communication models. The US AF and USN agreed upon the development of a Weapon Server Common Environment (WSCE) framework as a joint framework to house weapon models. This effort is led by the US Navy and supports the training community. Electronic warfare effects are generally a function of the specific system and model features of the SUT. These effects are categorized and validated through

Laboratory or Open-Air Range testing. Cyber effects generally follow the same approach as electronic warfare requiring laboratory or range testing to validate an effect for simulation use. Finally, space models run the gambit from commercial space to military space systems. JSE is focusing on the use of Space in support of the air system that would generally include communication and navigation models.

A final note, given the object oriented and/or composable nature of the JSE, models can be rapidly replaced within the architecture (as an edge service), as long as edge service simulations comply to the JSE distributed simulation architecture. This flexibility forms the basis for reuse across the community providing useable and tailorable capability across multiple domains.

3.2 JSE in Operation for Air Force Test

The JSE Operational view is shown in Figure 2. The following descriptions define the JSE key “service” components. Services contained within the Information Broker, the IESM, which support the agnostic operation of the broker itself, are labelled as “core” services. Services that ensure a fair fight are “common services.” Services that allow the user to set up and execute the simulation are “exercise services.” Services that provide entity or domain specific characteristics are “edge services.”

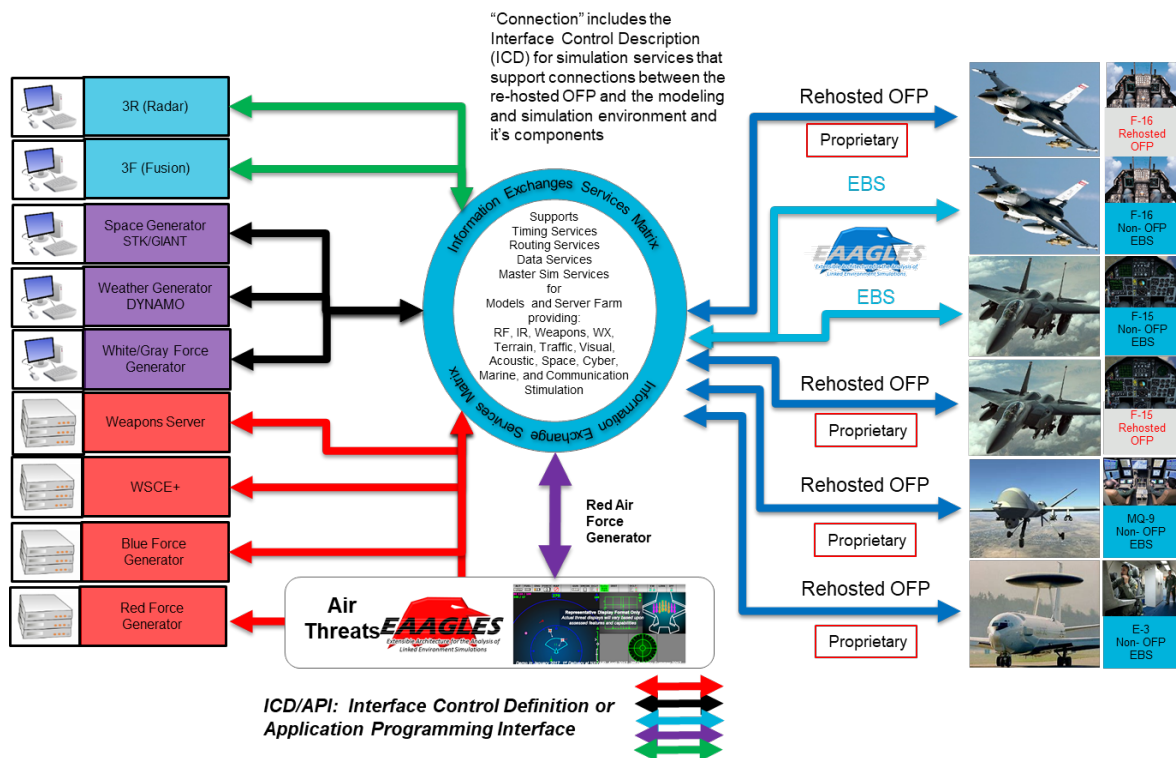


Figure 2. JSE Operational View for Air Force Testing

Following these definitions, simulation applications representing weapon systems are considered edge Services. The IESM broker provides core services to the simulation environment and interfaces with common and edge services. Common services include RF and IR environments, weather, munition models, communication models, etc. Other services (which are analytical, infrastructure, or exercise support related) include analytical services, data and interface repositories, standards repositories, and operational missions/use cases, etc.

Figure 2 illustrates the various edge services within the JSE. The core services, contained within the IESM allow the various services within the JSE to operate in a manner that is seamless to the user. The intent of the exercise services are to allow a JSE user to plan a mission using the appropriate operationally relevant mission planning tools. Once planned, a blueprint is formed that can be passed to a simulation engineer to support the orchestration of the simulation environment by assigning needed functionality to available components/services. This operation is transparent to an operational user, but critical to a tester or trainer to ensure the proper fidelity to support the test or training requirement is available and aligned with the simulation assets/services. After orchestration, test or training personnel execute the mature blue print. Collected data is analysed for test or training purposes.

While Figure 2 illustrates a “clean” design in which the community builds simulation components according to the design, implementation within the existing infrastructure provides a more realistic view of maturation of the JSE over time. Many training systems within the current training portfolio utilize rehosted Operational Flight Program (OFP) code in representing the system. These legacy systems utilize system OFP wrapped with a simulation interface to interoperate with the training environment. The JSE must provide a means to integrate new and legacy OFP and non-OFP simulators of numerous fidelities into a seamless battlespace. The JSE interface documents and services must address the information exchanges required between the system edge services and the battlespace common services to form a coherent unified battlespace suitable for test and training support. Figure 3 provides an illustration of these components while highlighting the need for Interface Control Descriptions (ICDs) to manage message interactions between these diverse services.

Finally, the environment must provide an integration path for additional edge and/or common services such as Space, Cyber, Communication, and Weapons. These services are likely to be a mixture of both common services and application unique edge services when the SUT or Training requirements demand. As with many common services, JSE seeks to accommodate multiple configurations with Government-Off-The-Shelf (GOTS), Commercial-Off-The-Shelf (COTS), and Industry proprietary solutions (unique edge services). This is a potential collaboration area between NATO partners.

3.3 Putting the Pieces Together

The JSE will start with an established prototype using work performed by the team in support of other activities conducted at Patuxent River NAS with NAVAIR. The expansion of the prototype capabilities leverages work performed by the MITRE Corporation in establishing the Information Exchange Services Matrix (IESM) while maturing other critical components. The prototype facilities at MITRE, the Simulation Analysis Facility located at Wright Patterson AFB, a test facility located at Edwards AFB, and the use of laboratory space at Nellis AFB will allow the team to continue development while remaining linked to the original prototype activities with the Navy at Patuxent River. This cross AF and Navy link, coupled with the continued threat model development by the Intelligence agencies provide ample mature components to populate the prototype as it matures. Figure 3 provides additional detail of the major components addressed in the prototype to allow the development activity to mature in support of test objectives.

Of particular interest is the maturation and integration of Region “A” Edge Services (Aircraft System models using rehosted OFP and higher fidelity simulators) coupled with common services (RF Environment, IR Environment, Line-Of-Sight (LOS), Weather, Weapons, and Electronic Warfare (EW)) driven by core services (via the IESM) through defined interfaces (ICDs/APIs). Additional Region “A/B” Edge Services include the use of the Next Generation Threat Simulation (NGTS) and other IADs models to provide a broad, complex, and dense test environment. See Figure 3.

One of the first challenges in maturing the prototype is the design and population of the ICD between the various edge services (Rehosted OFP, higher fidelity simulators) and the IESM. The Rehosted OFP aircraft simulation requires the tracking and/or fusion algorithms fed in at the appropriate rates with the appropriate

formatted data to ensure proper operation. Failure to meet these real-time requirements will render the test and/or training results invalid. This Quality of Service (QoS) requirement provides a speed and fidelity requirement that the IESM must meet in every time step important to the operation of the rehosted OFP within the system model. These requirements are captured by the IESM during the design and orchestration phases and result is the selection of higher speed services and networks. The IESM is designed to address multiple simultaneous channels of varying QoS to support the simulation.

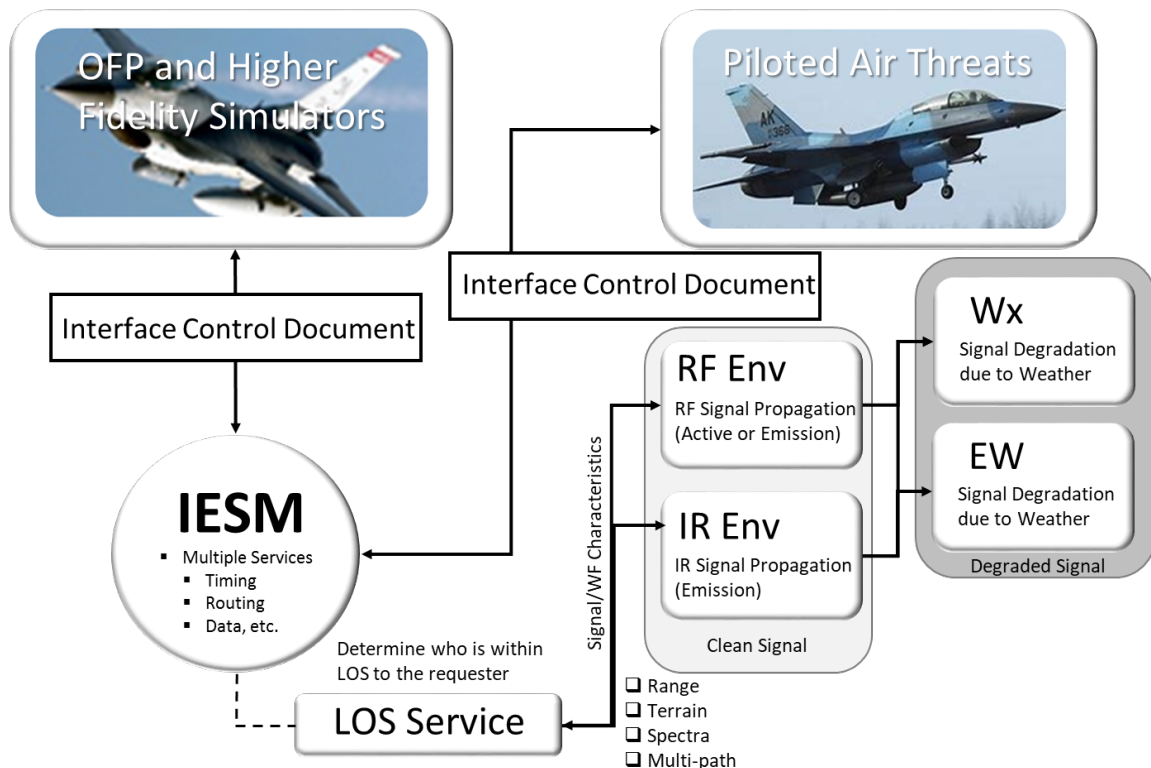


Figure 3. JSE Architectural view

The ICDs are part of the infrastructure within ICD repositories. The AF intends to define Government Simulation Interfaces (GSI) for the JSE that meet AF test needs. While the Government standards will allow the JSE to supply these standards to any Government Program Office in an unrestricted manner, they do not guarantee that all ICDs will be non-proprietary. The Government fully expects some Prime Weapon System Contractors (PWSCs) will establish propriety ICDs for their various rehosted OFP system models with the claim that the data fields contained within the ICD provide critical insight into the aircraft system model itself warranting the proprietary claim. As JSE balances cost and risk during development, it must also consider existing legacy solutions in the design.

The Government intends to allow the distribution of the GSI libraries to the Program Offices to support the distributed development of numerous aircraft system models using rehosted OFP that are compliant with the JSE. This provides a long-term business case for the Government supporting edge service development within the program offices while the Government supports a reusable, composable, common, and Government owned simulation environment suitable for all program use. The use of a Government owned environment levels the playing field by ensuring assessments contain transparent, well-understood, and government developed and controlled common services.

4.0 MODEL/ENVIRONMENT VERIFICATION AND VALIDATION

4.1 Establishing the Verification and Validation Foundation for Modelling and Simulation

The crux of using a Modelling and Simulation environment for test purposes relies upon its credibility with the decision-making test body. By its very nature, Modelling and Simulation generally utilizes assumptions to focus modelling efforts on features and functions within the system/environment believed to be critical in supporting the test objectives. This approach serves multiple purposes including focusing limited dollars and effort on areas that are believed to be critical drivers in assessing test objectives while balancing cost and risk in developing only as much functionality and fidelity as required to support a credible test activity. The decisions into which features and functions are critical to a test form the central issue in building a JSE. How much fidelity is required and for what test objective/purpose? There comes a point where adding too much functionality or fidelity is not only unnecessary, but can be detrimental to an analysis by confounding critical factors and making the design of experiments, and resulting analysis, unnecessarily complex.

The JSE seeks to utilize proven Operations Research (OR) based analytical techniques and practices coupled with state-of-the-art tools and infrastructure. JSE will leverage the practice of executable architectures to allow the design/user to assess information exchanges within the requirement analysis space verifying that these data exchanges will satisfy the information exchange requirements. This is an early and critical step as part of the Verification and Validation activities the JSE must support.

4.2 Message Exchange Characterization

The JSE team is assessing various tool capabilities to determine the best tool(s) to support environment needs. One of the critical decisions, that must be carefully weighed and balanced, is to how much detail and to what depth the exchange messages/requirements are defined within the executable architecture. Trades include (1) Open loop or Closed loop or both, (2) Basic equations for sensor detection or complex equations including switches and filtering, (3) Message exchange content, (4) Message exchange context within the use case or mission-based use case, and (5) Sensor model characteristics pertinent to the exchange, etc. This can be a long and detailed list with numerous branches in describing information exchanges. The difficult task is deciding how much detail is enough, where to trim the many possible exchange conditions (branches), and the criteria as to when and how you decide to trim the branches.

One of the significant challenges in integrating diverse simulation components and/or environment generators is the harmonization of the components relevant to detail and resolution. Without proper harmonization, JSE does not end up with valid results or a “fair fight” as some models will not properly process the erroneous data. As an example, the sensor model of a radar might include differing forms of the radar range equation, filtering, differing characterization of the radar modes, signal processing, etc. These differences may affect the common services and how messages are treated as they propagate within the environment. Design of the JSE services must provide enough flexibility to not only support the message exchanges, but account for known and likely variances in the edge service providers and consumers of those messages. [5]

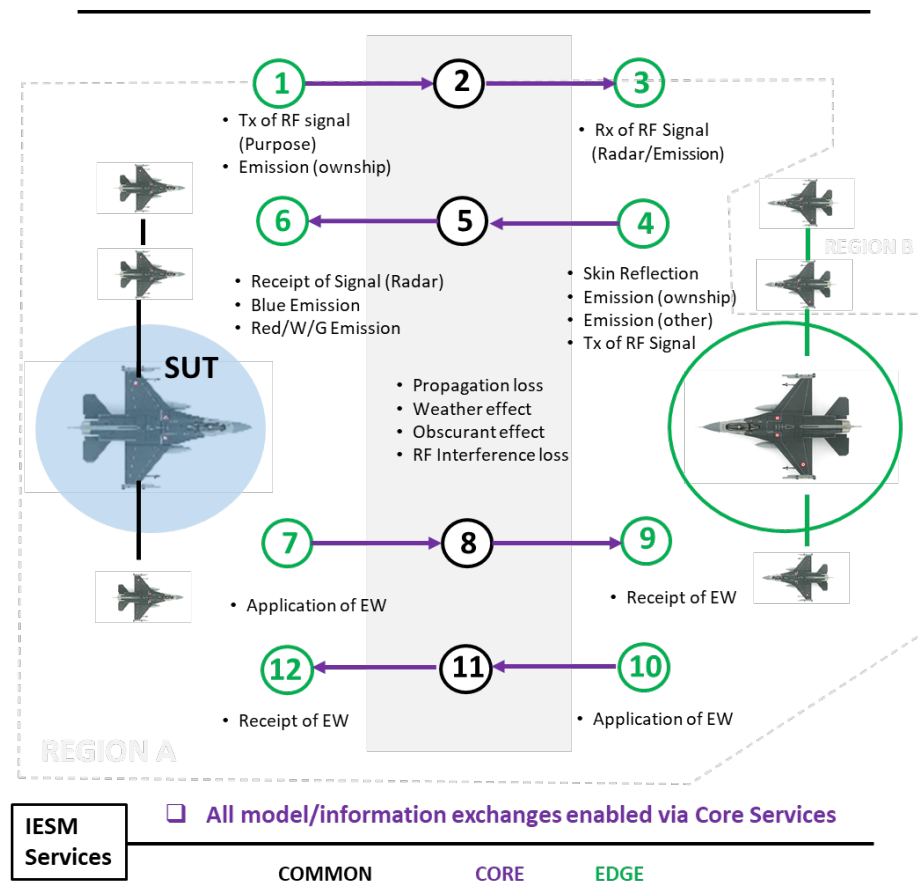


Figure 4. JSE RF Exchange Example

Figure 4 describes the type of exchanges present in a typical engagement: 1. The edge service representing the system under test computes the Tx of the RF signal to detect/track the opposing system. 2. Using the core services provided by the IESM, the edge services call the common service to calculate propagation loss, weather effects, etc. 3. The common services provide the resultant Rx and RF signals to the edge service representing the opposing system. 4. The skin reflection from the opposing system is computed by the common service but the resulting track is evaluated at the appropriate edge service. 5. The resulting signals are modified accordingly by the common services and the results are exchanged with the SUT. 6. The SUT receives the modified signals and computes the detection/tracking characteristics for the SUT. 7. Based on the results, the SUT decides to apply EW means and invokes the common services to modify the emission accordingly. 8. The common service applies the appropriate effects/computations to the EW RF signal as it propagates through space. 9. The opposing system, via the common services, receives the modified EW signal and determines the effect of that signal on the system in the local appropriate edge service. 10. The opposing system, via the edge service, applies EW against the SUT and invokes common services. 11. The common services modify the EW signal to account for RF propagation, weather, etc. 12. The SUT receives the modified RF EW Signal via the common services and, through its services, determines the effect of the EW signal on the SUT.

Ideally, JSE would have the radar modelling characteristics for the generation and detection of an RF signal. Typically, a form of the radar range equation is modelled with additional considerations for processing choices or other unique aspects of the radar characteristics and resulting performance. JSE will utilize an RF environment to account for RF signal loss when propagated through space. Additional atmospheric parameters would include weather effects (moisture, etc.), Obscurants (smoke, etc.), and RF interference loss

from other RF energy propagating in the atmosphere. Receipt of the RF signal at the threat source would account for these losses and present RF parameters to the threat for RF signal detection and to present the necessary parameters to form an RF skin return (radar cross section) to support a detection calculation by the transmitting radar. Where these calculations actually occur in the JSE is a function of numerous considerations including the existing architecture of some of the system models, computational complexity, enterprise view of the desired long-term architecture, anticipated required fidelity, and impact to existing models and product lines within the community. The RF exchange example in figure 4 above will likely evolve as the IESM architecture matures.

The use of an executable architecture would allow the requirements team (as well as the V&V team) the ability to assess the completeness of the requirements necessary to support the modelling, simulation, and analysis objectives. Additionally, the executable architecture provides a coarse check on the modelling and simulation environment by comparing information-exchanges via use-cases. The executable architecture documents the requirement while providing a means to dynamically assess the execution of the information through the interfaces. Results from the execution of the simulation verify that the exchanges are properly documented in the architecture tool as part of the Operational and/or Developmental V&V activities conducted prior to testing.

4.3 Desired Features of an Executable Architecture

JSE will use commercially available executable architecture tools to support the development activity such as Enterprise Architect, Magic Draw and other SYSML/UML capable tools. The Air Force's intent is to describe the message interactions within the JSE by spectrum/band (RF, IR, Visual) as they relate to the various IESM Services (Core, Common, Edge, Exercise). These interactions will be developed and documented in the tools and then verified and validated against flight test, hardware in the loop (HITL), or anechoic chamber data as those components are developed and/or integrated and tested. From a prioritization perspective, Region "A" will take precedence over Regions "B" and "C." The use of executable architecture tools provides a means of developing, documenting, and testing not only the information exchanges, but the collection of information exchanges and corresponding required Quality of Service (QoS) necessary to populate the ICDs for the simulation. Reuse of the ICD's allows other Programs within the Air Force, other services, and partners to design their simulations against the ICDs and ensure interoperability with the JSE.

JSE also requires features tailored for the unique aspects of the architecture including the ability to link and track requirements based upon characteristics and features defined in the IESM. As previously described, the IESM decomposes the Information Broker into four service classes: Core, Common, Edge, and Exercise.

Recapping the previously described services, the core services are essential to all services and entities, are intricately linked, provide basic information broker functionality such as timing, routing, object declaration, object management, security, etc. Common Services ensure a fair fight and include RF, IR, Weather, Weapons, etc. Edge services provide functionality required by the JSE to support mission execution such as system representations, or unique components within the environment, etc. Finally, exercise services allow the user to define, configure, execute, and analyse the results from the environment. Exercise services would include mission planning, environment composition, orchestration, execution, and analysis.

Returning to Figure 4, and the information exchange example, the colors in the figure illustrate the various services involved in supporting an information exchange. In this example, timing, not shown in the figure, could readily be added in the form of quality of service (QOS) requirements. As written, the fighter aircraft shown within the figure are Edge Services and provide necessary war-fighting functionality to the test event. Common Services, represented in Black, illustrate the universal components required by all players within the environment to ensure a "fair fight". Common representations of universal services prevent inconsistencies in the representation of these services by establishing a single service to meet all entity needs.

The Violet color represents the routing paths required within the JSE for message exchanges and are Core Services. Core Services provide a variety of services as well as routing via information paths necessary to support Quality-Of-Service timing requirements. Conducting a complete test as illustrated in Figure 4 would be an example of an Exercise Service.

The ability to analyze not only the information exchanges, but also the Quality of Service required and provided within the executable architecture is an example of a custom requirement that the AF seeks within executable architecture tools. The Air Force intends to continue to drive the development of these tools to ensure the JSE needs are met while advancing its ability to rapidly characterize the performance of the environment in supporting Verification and Validation requirements for Test and Training.

5.0 DISCUSSION AND SUMMARY

The decision by test community leadership within the USAF and USN provides the community with an opportunity to advance the state-of-the-art in the design, integration, and application of a Virtual-Constructive real-time environment for test and training purposes. The leadership recognizes the limitations in today's physical test ranges in supporting current and future testing requirements in an environment that continues to expand its reliance on advanced sensors, datalinks, automation, and other technologies that do not readily lend themselves to live open-air-range testing. This recognition provides an opportunity to leverage significant investment already made in advancing Modelling and Simulation capabilities developing new capabilities only as required to meet Test and Training objectives. This risk-balanced approach avoids the pitfalls of many previous attempts to leverage Modelling and Simulation technologies by forming a composable environment that relies on proven technologies and established capabilities as opposed to constructing a complete a new environment fraught with development and cost risks.

JSE provides sharp contrast with previous efforts in another manner. JSE is a teaming activity leveraging the community investment in the JSE while accommodating individual service needs via a composable government-owned architecture and associated environment. The broader JSE Team provides a means to work across military service boundaries via that common architecture while allowing the military services to tailor the edge or exercise services as required. The core and common service are consistent and in fact, many of the edge and exercises services may remain consistent across the military services, but the key is that they do not have to do so. The military service partners have the inherent flexibility built into the architecture to tailor the architecture components depending upon their unique requirements and/or applications.

This paper has touched the basic tenants of the JSE. A complimentary paper by Dr. Andreas Tolk, the MITRE Corporation, provides an overview of the heart of the JSE, namely, the Information Exchange Services Matrix (or IESM). The IESM provides necessary services to the JSE allowing the various components within the JSE to function seamlessly with the ultimate objective of a complete integrated battlespace for Test and Training. [4] While the JSE today utilizes, the Global Reference Information Directory or GRID, the next generation of JSE development will expand the GRID to become the IESM.

In conclusion, the objective of this paper is to both produce knowledge for the reader and to solicit new ideas from the community to continue to advance modelling and simulation state-of-the-art for test and training applications by collaborating with our NATO Allies.

6.0 ACKNOWLEDGEMENTS

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Joint Simulation Environment for United States Air Force Test Support

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ABSTRACT

Advances in integrated, multi-domain warfighting capabilities are challenging the ability of militaries to rapidly design, develop, field, support, test, and train next generation war fighting capabilities. Today's physical test ranges, in their present form, are inadequate to meet the testing and training needs of these future integrated weapon systems. Future test capabilities must be augmented with state-of-the-art modelling and simulation technologies to form a virtual range capable of meeting development, test, and training needs in a rapid and cost-effective manner. The United States Air Force, in concert with our Service partners, intends to develop an integrated modelling and simulation based virtual test range to address these challenges. The Joint Simulation Environment (JSE) leverages lessons learned from recent modelling and simulation activities in support of Joint Air Force and Navy testing. JSE seeks to advance the state of the art in modelling and simulation technologies applied to test, training, and experimentation. This paper will discuss JSE use in supporting Air Force objectives, challenges, way-forward, and potential NATO Partnership opportunities.

1.0 INTRODUCTION

The overall vision for the Air Force for the JSE capability is to improve developmental and operational test quality and efficiency, provide a stable and secure environment for cross-platform advanced training and tactics development, and better inform future acquisition decisions by improving the quality of integrated force analysis of alternative studies via multiple fidelity level experimentation and capability demonstration. Specific JSE objectives include:

- (1) A government-owned, multi-platform advanced M&S capability that overcomes existing open-air range limitations, to include system availability, threat density, and safety and security concerns.
- (2) An open architecture that enables composability and integration of models and simulations of varying levels of fidelity, to include blue and red aircraft operators-in-the-loop, threats, weapons, terrain and weather.
- (3) Interoperability with other services and foreign partners within the JSE and extension to other required simulation environments.
- (4) Opportunity for international testing and training/experimentation.

The overall goal of JSE is to enable smarter, faster acquisition by providing data in order to enable war fighter and acquisition decision makers to make risk-informed decisions in support of the recently published U.S. National Defense Strategy. *Dr. Eileen A. Bjorkman, Deputy Director of Test and Evaluation*

Air Force leadership recognized the need to provide a credible test environment to support current and future system testing, not currently possible on current test ranges due to a number of limiting factors. These factors include geographical constraints, technology limitations, electronic warfare limitations, frequency spectrum interference, operational limitations, and safety concerns. Reviewing these factors is instructive since they form or significantly contribute to the requirements foundation of the JSE for the Air Force.

2.0 JSE REQUIREMENTS

In 2017, the Chief of Staff of the Air Force (CSAF) directed the AF community to pursue a synthetic test capability designed to address current and future test and training deficiencies. The funding for this effort, provided by the AF to support the development activities and a lead execution organization (412th TW at Edwards AFB) within the test community, was established starting in Fiscal Year 2019. The Air Force Test and Evaluation Office (AF/TE) directed the team to develop and field a synthetic test capability by FY23 at both Edwards and Nellis AFBs. This effort links with the development of the synthetic test environment currently in development at Patuxent River NAS using a joint USN, USAF, and Intelligence Agency team.

The requirements development effort addresses three primary areas: (1) test limitations within today's physical test ranges, (2) anticipation of future capabilities and associated needs, and (3) balancing of cost and risk in achieving a useable and flexible design that can readily grow in time.

2.1 Limitations on today's test ranges

- Geographical constraints affect the ability of the live assets to properly set up the engagement, employ longer-range weapons, maneuver, or employ CONOPS/TTPs within larger mission fleets/forces against an air or ground threat system or integrated air defense system (IADS).
- Technology limitations limit the integration of live assets with modelling and simulation entities in the execution of test objectives. While the Test community has utilized synthetic environments for numerous years on the test ranges to augment a live force, significant technology-based obstacles exist that limit the effectiveness of the synthetic environment, such as the inability to replicate a dense threat environment employing complex signals in real time.
- Electronic Warfare Limitations include the replication of dense and complex electronic warfare environments in real time within a digital format. Achieving this computationally challenging environment through the use of complex fully digital signals would allow the simulation world to rapidly and cost-effectively scale the environment and be more representative of today's battlespace.
- Frequency Spectrum Interference limits today's test ranges in the type, and strength of electronic signals permissible on the range. This may include not only electronic warfare signals, but also IFF and RF communications that are not bound to range physical characteristics and may be adjacent to commercial frequency spectrums causing unintended electromagnetic spill over.
- Operational Limitations prevent the full range of possible engagements within a Mission Effects or Kill Chain. The most obvious limitation is the safety-driven limitation of the use of live weapons in close proximity to manned systems to complete the Kill Chain or engagement on a test range.
- Safety Concerns address not only the inability to utilize weapons, but also complex engagements of multiple aircraft aggressively manoeuvring in a confined airspace and with terrain considerations. Range safety is a primary concern when testing aircraft and routinely provide test limitations that can adversely affect test results.

The JSE seeks to remove or limit these constraints by developing a virtual test range to augment the existing physical ranges when testing systems or system of systems.

2.2 Anticipation of future system test needs

Next generation testing will encompass not only advanced systems and weaponry, but also the need for systems to work in close coordination (between US and NATO partners) within an information-based system of systems. Information technologies will provide broadband, high-speed connectivity that will enable shared information-based applications to support improved detection, tracking, identification, and weapon delivery solutions. A future synthetic test range may be the only viable means to test a future information-

based system/system-of-system kill chain. Viability implies not only the ability to test the technologies, but to do so in a cost-effective, risk-mitigated, and complete (full kill chain) manner. Future test needs may include:

- **Battlespace Density/Complexity:** The synthetic range must be able to produce large numbers of assets of varying complexity to properly “feed” the System-Under-Test (SUT) in a credible battlespace environment to support the necessary and appropriate test conditions. These feeds are a combination of virtual and constructive entities from a variety of simulation capabilities in a distributed environment.
- **Geo-Specific Place/Time Testing:** The synthetic range must be able to replicate geo-specific terrain on any test range or in any area of the world. This capability must include not only the support of non-imaged sensors, but also image-based sensors including cultural features and threats/targets-of-interest to the test community. An additional requirement is to replicate this geo-specific place within varying time spans from current year to any number of future projected years.
- **Representation of Future Rapid and Adaptive Threat Capabilities:** The synthetic range must be able to produce a realistic representation of future threats and the resulting interaction with the System Under Test (SUT). Stapleton observed that we do not realistically represent technologies within our tests often substituting current technologies in place of future technologies that are not well understood, or similarly, future effects that are not well understood. This pattern is often repeated with regard to our future threat representations, resulting in unrealistic own and opposing forces pairings under unrealistic engagement conditions. As more systems increasingly rely upon easily upgradable software this trend becomes more pervasive in our testing. [1]
- **Multi-Domain Integration:** The synthetic range must be able to produce the ability to test the kill chain across multiple domains including air, space, sea, land, and cyber. The synthetic test range must address the multi-domain aspects of future systems and their associated war fighting capabilities. Additionally, the nature of a multi-domain, multi-national, complex array of sensors distributed across the air, space, and cyber domains presents a daunting test challenge. New approaches and methodologies are required to address the complexity challenge such as those suggested by Sheard. [2]
- **Future Kill Chain:** The synthetic range must be able to produce the ability to test the kill chain from detection (on-board or off-board ISR sources) through tracking, through identification (ID), to targeting, and through Battle Damage Assessment (BDA). Enabling a cross discipline kill chain involves moving from air/space/sea/land/cyber target detection via advanced sensors, data processing, data mining, networking, cueing, track formation and sustainment, track correlation, track fusion including ID from diverse information sources, rapid decision-making with support from automation, and Artificial Intelligence. While it is possible to deconstruct a test into sub-objectives, the entire kill chain must be testable within a synthetic range.
- **Collaboration:** A future kill chain may elect to combine steps within today’s kill chain reducing the need to share the information across network spaces or it may elect to enable many spectrally diverse sensors located on various platforms and in effect expand the kill chain collaboration. This collapse and expansion might occur dynamically during the prosecution of a mission and be accelerated by automation. Support platforms/sensors or nodes owned by US or US Partners (NATO) must work in collaboration within this dynamic battlespace. Additionally, US/US Partners must communicate and dynamically and rapidly share raw and/or processed information. The Command and Control (C2) aspects of a future fight will require a higher degree of decision-making collaboration that must keep pace with a highly dynamic and time constrained modern battlespace while addressing collaboration barriers (such as language). A synthetic range must be able to support the testing of these challenges from providing credible sensor modelling, to connectivity, to addressing rapid and dynamic decision-making requirements.

- **Automation:** Future warfighting systems will continue to see improved automation requiring test capabilities to support various levels of autonomy from pilot assisted autonomy to complete machine-to-machine autonomy requiring no human intervention. These varying levels of automation located throughout the kill chain provide significant challenges to the tester with or without a synthetic test range.
- **Geo-Specific Weather:** While a physical range cannot control the weather, a synthetic range can provide dynamic and varying weather conditions within the testing environment. A synthetic range must provide the ability to produce and alter weather conditions within the test environment that correlates non-imaged and imaged sensors, networks, and nodes.
- **Electronic Warfare (EW):** A synthetic range can avoid the EW issues found on physical ranges. The synthetic EW signal is not observable by our enemies (not propagated in physical space), does not infringe on commercial spectrums, and can be readily modifiable as desired. There are four principle challenges for Modelling and Simulation today when employing EW techniques: (1) Generating and propagating signal complexity in real time in a dense EW environment, (2) Scaling EW signals in space, (3) Verification and Validation of the EW signals and their effect within the environment, and (4) properly modelling the Electronic Attack and Electronic Protection interactions given the available fidelity in today's models.
- **Security:** A synthetic range must address security concerns as various programs interoperate within a common operational battlespace. Multi-Level-Security (MLS) concerns are central to the development and operation of the test range. MLS concerns are addressed early in the design and potential solutions will only consider proven and previously approved approaches.

2.3 Balancing Cost and Risk

Achieving a viable synthetic test range design and implementation approach requires the architect to balance available modelling and simulation technologies with development and sustainment cost and risk. The AF budget established cost numbers for the development effort. The AF development team elected to balance the design of the JSE in the following manner:

- **Use of an existing prototype:** The JSE for broad AF use must expand capabilities from an existing environment developed jointly by the Navy and AF to support broad operational testing activities. The Joint Navy, AF, and Intelligence community team constructed this first environment, led by the Navy, at Patuxent River Naval Air Station (NAS) located in Maryland, United States. Using a working prototype allows the team to continue development and the Air Force to leverage these prior investments while mitigating development risk.
- **Limited Development:** The Air Force elected to limit environment development where practical by reusing models/components within the existing environment. The current reuse is over 60% within the environment. Sixty percent (60%) of the models the Air Force intends to use are already developed and in use within the community of interest. Of the remaining development items, 20% are currently in development, with the remaining items scheduled to start development in FY20.
- **The System-Under-Test (SUT)** will generally contain rehosted Operational Flight Program (OFP) code supplied by the appropriate System Program Office. The developing contractor must work with the Government JSE team to integrate the SUT with the JSE environment. These costs and risks are appropriately aligned with the System Program Office and Prime Weapon System Contractor.
- **Development of an Information Broker** that is responsible for the proper message exchanges supporting the necessary timing, scheduling, routing, and other services is critical to ensuring the synthetic test range operates as designed. For the next iteration of the JSE, this Information Broker is known as the Information Exchange Services Matrix (IESM). The IESM is information/domain

agnostic and can be utilized for not only test, but also training and experimentation uses. The IESM is the subject of a separate paper produced by the MITRE Corporation.

- **Distributed Operations:** There is a desire within the test and training community to connect geographically distributed sites, cost-effectively enabling larger and more diverse testing and training including cross-service components. This requirement is not contained within the initial JSE development effort, but the synthetic range design will provide design accommodations to ensure the range can support distributed operations in the near future. This requirement is balancing cost and development risk by early accommodation of distributed operation needs in the design coupled with early prototyping.
- **Blending of Commercial and Government Off-The-Shelf (COTS/GOTS) products** while limiting new development to only those critical capabilities without which the JSE cannot succeed: This risk-managed approach allows JSE to establish an early baseline from which to measure development progress while balancing risk and cost. While the JSE is government-owned, its composable nature allows for the addition of commercial and even proprietary components as required. All solutions must provide specific metadata that provides the needed conceptual and technical transparency of the solution needed to ensure integration into the infrastructure, interoperability of the simulations, and composability of the concepts. [4]
- **Development with the goal of NATO Allies collaborative development and use:** Foundational architecture and software decisions allow the sharing of capability with US allies supporting an objective of collaborative development and use for Test and Training applications. This approach fundamentally changes the technological decisions for the development of the JSE.

Collaboration comes in many forms. The sharing of ideas provides an idea trade space from which to formulate a longer-term collaborative implementation plan. Collaboration can include the cooperative design of common components that provide a foundation for interoperability. In addition, collaboration can result in the joint development of critical components that enable allies to employ operationally relevant CONOPS vis-a-vie integrated or integratable simulation environments.

3.0 JSE ARCHITECTURE APPROACH

The approach selected by the Air Force to utilize and further contribute in developing the synthetic environment begins by defining three regions. Region A is the region where the System-Under-Test (SUT) resides and any other entity or component critical to the testing of the SUT. Entities in Region A have direct interaction with the SUT. Region B entities can have a direct influence on the SUT and may or may not directly interact with the SUT under limited circumstances. Region C entities provide context to the broader scenario and do not directly interact with the SUT.

The idea captured in the development of Regions A, B, and C follows best practices for system engineering. In systems engineering, there is great interest in achieving precise detail in high resolution and fidelity in our system within the system borders (Region A). There are other systems that the SUT has to interact with, but at a lesser fidelity (lesser impact to the SUT performance) (Region B). Finally, there is the context that provides the additional input and may influence our system, but is not influenced by our system (Region C). [3]

REGION A:

- ✓ System Under Test (SUT)
- ✓ Virtual Air Threats (VAT)
- ✓ Lower Fidelity Blue Simulators
- ✓ Weapon Models
- ✓ Common Services required to support the SUT
- ✓ Threat Components
- ✓ Analytic Services

REGION B:

- ✓ "Stand By" Virtual Air Threats (VAT)
- ✓ Lower Fidelity Blue System Models
- ✓ Blue Constructive Entity Generator
- ✓ Threat Constructive Entity Generator

REGION C:

- ✓ Low Fidelity Constructive Air Entities for Battlespace Context

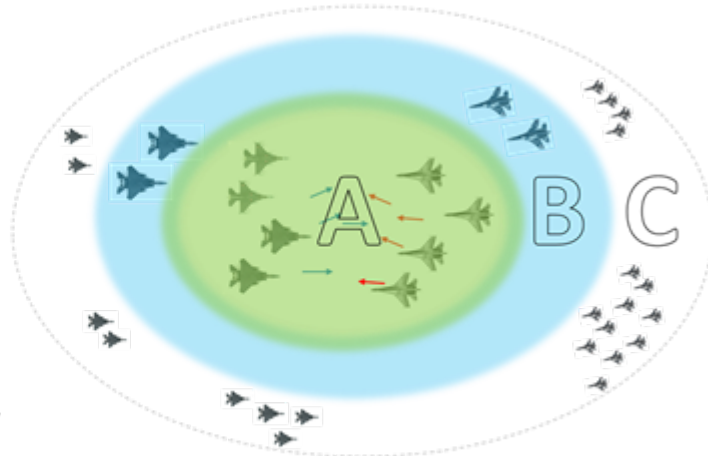


Figure 1: JSE Test Region Description

3.1 Composition of the JSE Architecture

The JSE Architecture approach is to decompose the environment into a limited number of components from which to enable multiple and concurrent development streams. Each component contains a specific suite of requirements necessary to enable select functionality within the environment. The major components will include:

- Representation of own systems in high fidelity
- Representations of opposing systems in high fidelity
- Consistent representation of the environment
- Consistent representation of interactions between these systems in high fidelity
- Representations of own systems in lower fidelity to provide a credible test environment
- Representations of opposing systems in lower fidelity to provide a credible test environment
- Administrative, Infrastructure, Data Collection, Analysis Tools, and other Exercise supporting services

As the JSE designs and implements common services, it would be wise to consider the NATO objectives of interoperable forces. NATO forces must be developed within the collaborative employment and operation in combat theatres. It follows that collaborative test and training is required to meet these objectives. The development of common services includes the development of RF/IR environments, RF-based communication, weapon models/effects, electronic warfare effects, cyber effects, and space models/effects. The intent of the JSE is to allow the end user to alter edge services as required, but to develop an agnostic suite of common services to support a fair fight. JSE is utilizing RF/IR environment services from legacy system software, upgrading the code structure and modelling language to meet today's standards. The US Air Force has developed numerous higher fidelity communication models that will form the basis of the common communication models. The US AF and USN agreed upon the development of a Weapon Server Common Environment (WSCE) framework as a joint framework to house weapon models. This effort is led by the US Navy and supports the training community. Electronic warfare effects are generally a function of the specific system and model features of the SUT. These effects are categorized and validated through

Laboratory or Open-Air Range testing. Cyber effects generally follow the same approach as electronic warfare requiring laboratory or range testing to validate an effect for simulation use. Finally, space models run the gambit from commercial space to military space systems. JSE is focusing on the use of Space in support of the air system that would generally include communication and navigation models.

A final note, given the object oriented and/or composable nature of the JSE, models can be rapidly replaced within the architecture (as an edge service), as long as edge service simulations comply to the JSE distributed simulation architecture. This flexibility forms the basis for reuse across the community providing useable and tailorable capability across multiple domains.

3.2 JSE in Operation for Air Force Test

The JSE Operational view is shown in Figure 2. The following descriptions define the JSE key “service” components. Services contained within the Information Broker, the IESM, which support the agnostic operation of the broker itself, are labelled as “core” services. Services that ensure a fair fight are “common services.” Services that allow the user to set up and execute the simulation are “exercise services.” Services that provide entity or domain specific characteristics are “edge services.”

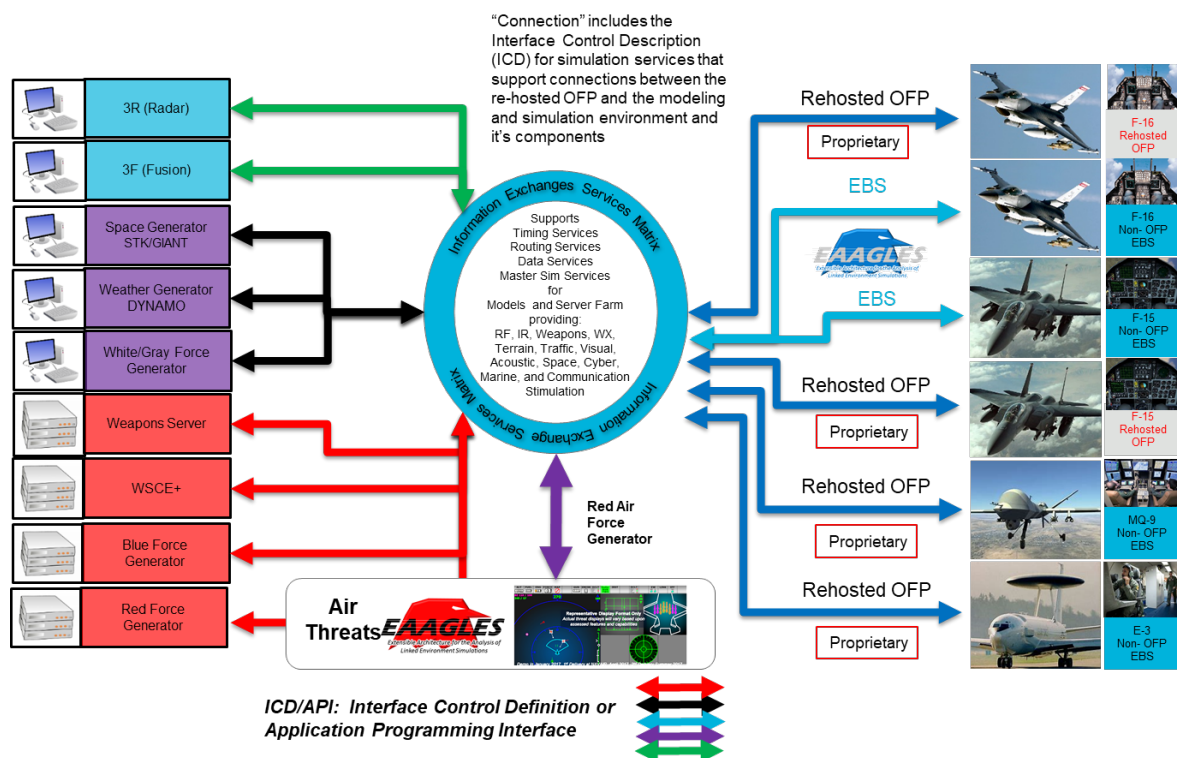


Figure 2. JSE Operational View for Air Force Testing

Following these definitions, simulation applications representing weapon systems are considered edge Services. The IESM broker provides core services to the simulation environment and interfaces with common and edge services. Common services include RF and IR environments, weather, munition models, communication models, etc. Other services (which are analytical, infrastructure, or exercise support related) include analytical services, data and interface repositories, standards repositories, and operational missions/use cases, etc.

Figure 2 illustrates the various edge services within the JSE. The core services, contained within the IESM allow the various services within the JSE to operate in a manner that is seamless to the user. The intent of the exercise services are to allow a JSE user to plan a mission using the appropriate operationally relevant mission planning tools. Once planned, a blueprint is formed that can be passed to a simulation engineer to support the orchestration of the simulation environment by assigning needed functionality to available components/services. This operation is transparent to an operational user, but critical to a tester or trainer to ensure the proper fidelity to support the test or training requirement is available and aligned with the simulation assets/services. After orchestration, test or training personnel execute the mature blue print. Collected data is analysed for test or training purposes.

While Figure 2 illustrates a “clean” design in which the community builds simulation components according to the design, implementation within the existing infrastructure provides a more realistic view of maturation of the JSE over time. Many training systems within the current training portfolio utilize rehosted Operational Flight Program (OFP) code in representing the system. These legacy systems utilize system OFP wrapped with a simulation interface to interoperate with the training environment. The JSE must provide a means to integrate new and legacy OFP and non-OFP simulators of numerous fidelities into a seamless battlespace. The JSE interface documents and services must address the information exchanges required between the system edge services and the battlespace common services to form a coherent unified battlespace suitable for test and training support. Figure 3 provides an illustration of these components while highlighting the need for Interface Control Descriptions (ICDs) to manage message interactions between these diverse services.

Finally, the environment must provide an integration path for additional edge and/or common services such as Space, Cyber, Communication, and Weapons. These services are likely to be a mixture of both common services and application unique edge services when the SUT or Training requirements demand. As with many common services, JSE seeks to accommodate multiple configurations with Government-Off-The-Shelf (GOTS), Commercial-Off-The-Shelf (COTS), and Industry proprietary solutions (unique edge services). This is a potential collaboration area between NATO partners.

3.3 Putting the Pieces Together

The JSE will start with an established prototype using work performed by the team in support of other activities conducted at Patuxent River NAS with NAVAIR. The expansion of the prototype capabilities leverages work performed by the MITRE Corporation in establishing the Information Exchange Services Matrix (IESM) while maturing other critical components. The prototype facilities at MITRE, the Simulation Analysis Facility located at Wright Patterson AFB, a test facility located at Edwards AFB, and the use of laboratory space at Nellis AFB will allow the team to continue development while remaining linked to the original prototype activities with the Navy at Patuxent River. This cross AF and Navy link, coupled with the continued threat model development by the Intelligence agencies provide ample mature components to populate the prototype as it matures. Figure 3 provides additional detail of the major components addressed in the prototype to allow the development activity to mature in support of test objectives.

Of particular interest is the maturation and integration of Region “A” Edge Services (Aircraft System models using rehosted OFP and higher fidelity simulators) coupled with common services (RF Environment, IR Environment, Line-Of-Sight (LOS), Weather, Weapons, and Electronic Warfare (EW)) driven by core services (via the IESM) through defined interfaces (ICDs/APIs). Additional Region “A/B” Edge Services include the use of the Next Generation Threat Simulation (NGTS) and other IADs models to provide a broad, complex, and dense test environment. See Figure 3.

One of the first challenges in maturing the prototype is the design and population of the ICD between the various edge services (Rehosted OFP, higher fidelity simulators) and the IESM. The Rehosted OFP aircraft simulation requires the tracking and/or fusion algorithms fed in at the appropriate rates with the appropriate

formatted data to ensure proper operation. Failure to meet these real-time requirements will render the test and/or training results invalid. This Quality of Service (QoS) requirement provides a speed and fidelity requirement that the IESM must meet in every time step important to the operation of the rehosted OFP within the system model. These requirements are captured by the IESM during the design and orchestration phases and result is the selection of higher speed services and networks. The IESM is designed to address multiple simultaneous channels of varying QoS to support the simulation.

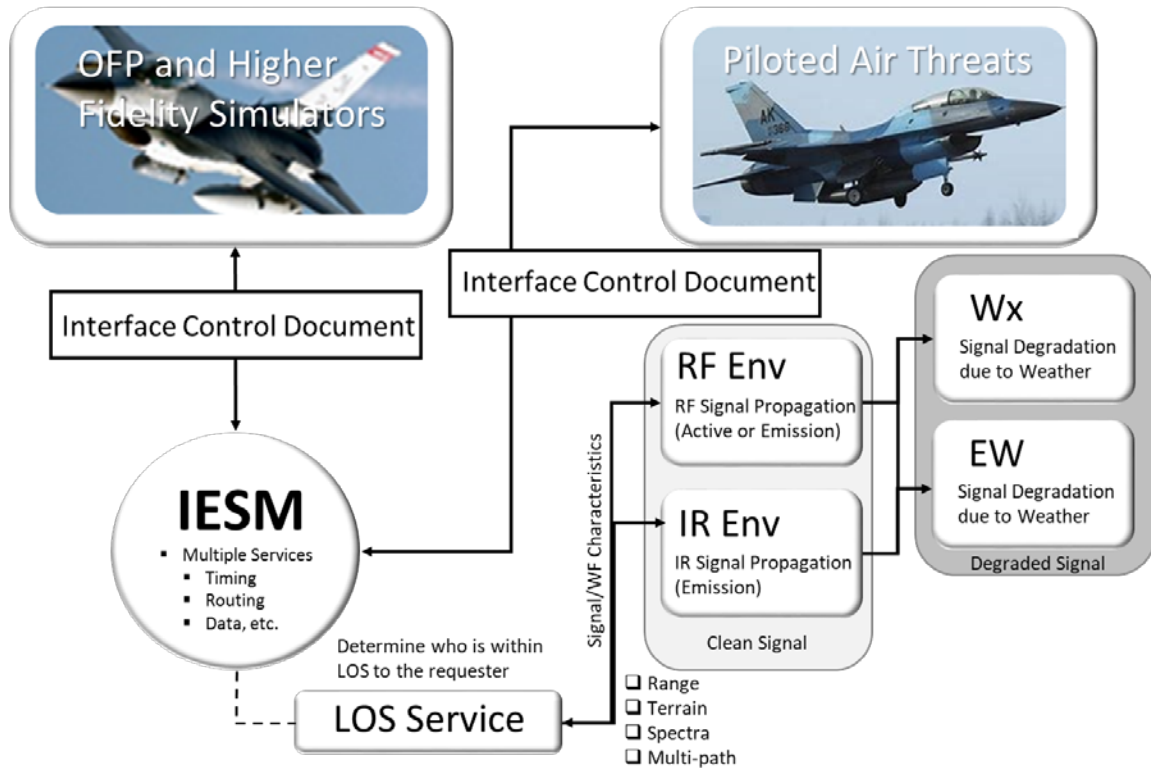


Figure 3. JSE Architectural view

The ICDs are part of the infrastructure within ICD repositories. The AF intends to define Government Simulation Interfaces (GSI) for the JSE that meet AF test needs. While the Government standards will allow the JSE to supply these standards to any Government Program Office in an unrestricted manner, they do not guarantee that all ICDs will be non-proprietary. The Government fully expects some Prime Weapon System Contractors (PWSCs) will establish propriety ICDs for their various rehosted OFP system models with the claim that the data fields contained within the ICD provide critical insight into the aircraft system model itself warranting the proprietary claim. As JSE balances cost and risk during development, it must also consider existing legacy solutions in the design.

The Government intends to allow the distribution of the GSI libraries to the Program Offices to support the distributed development of numerous aircraft system models using rehosted OFP that are compliant with the JSE. This provides a long-term business case for the Government supporting edge service development within the program offices while the Government supports a reusable, composable, common, and Government owned simulation environment suitable for all program use. The use of a Government owned environment levels the playing field by ensuring assessments contain transparent, well-understood, and government developed and controlled common services.

4.0 MODEL/ENVIRONMENT VERIFICATION AND VALIDATION

4.1 Establishing the Verification and Validation Foundation for Modelling and Simulation

The crux of using a Modelling and Simulation environment for test purposes relies upon its credibility with the decision-making test body. By its very nature, Modelling and Simulation generally utilizes assumptions to focus modelling efforts on features and functions within the system/environment believed to be critical in supporting the test objectives. This approach serves multiple purposes including focusing limited dollars and effort on areas that are believed to be critical drivers in assessing test objectives while balancing cost and risk in developing only as much functionality and fidelity as required to support a credible test activity. The decisions into which features and functions are critical to a test form the central issue in building a JSE. How much fidelity is required and for what test objective/purpose? There comes a point where adding too much functionality or fidelity is not only unnecessary, but can be detrimental to an analysis by confounding critical factors and making the design of experiments, and resulting analysis, unnecessarily complex.

The JSE seeks to utilize proven Operations Research (OR) based analytical techniques and practices coupled with state-of-the-art tools and infrastructure. JSE will leverage the practice of executable architectures to allow the design/user to assess information exchanges within the requirement analysis space verifying that these data exchanges will satisfy the information exchange requirements. This is an early and critical step as part of the Verification and Validation activities the JSE must support.

4.2 Message Exchange Characterization

The JSE team is assessing various tool capabilities to determine the best tool(s) to support environment needs. One of the critical decisions, that must be carefully weighed and balanced, is to how much detail and to what depth the exchange messages/requirements are defined within the executable architecture. Trades include (1) Open loop or Closed loop or both, (2) Basic equations for sensor detection or complex equations including switches and filtering, (3) Message exchange content, (4) Message exchange context within the use case or mission-based use case, and (5) Sensor model characteristics pertinent to the exchange, etc. This can be a long and detailed list with numerous branches in describing information exchanges. The difficult task is deciding how much detail is enough, where to trim the many possible exchange conditions (branches), and the criteria as to when and how you decide to trim the branches.

One of the significant challenges in integrating diverse simulation components and/or environment generators is the harmonization of the components relevant to detail and resolution. Without proper harmonization, JSE does not end up with valid results or a “fair fight” as some models will not properly process the erroneous data. As an example, the sensor model of a radar might include differing forms of the radar range equation, filtering, differing characterization of the radar modes, signal processing, etc. These differences may affect the common services and how messages are treated as they propagate within the environment. Design of the JSE services must provide enough flexibility to not only support the message exchanges, but account for known and likely variances in the edge service providers and consumers of those messages. [5]

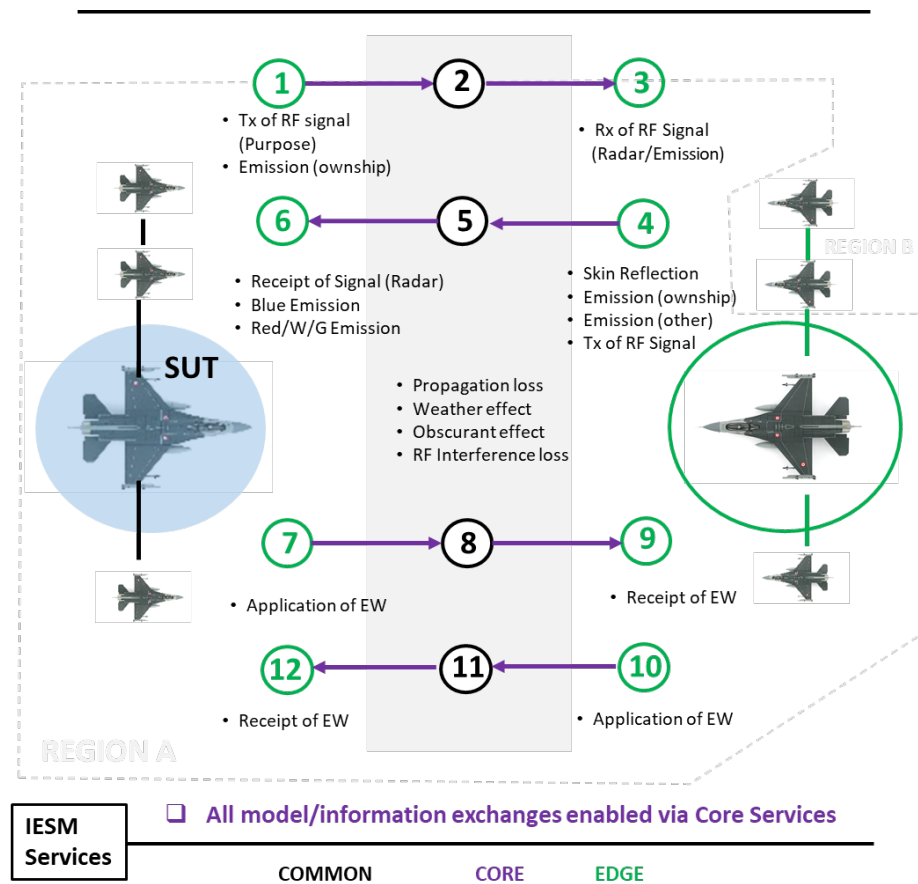


Figure 4. JSE RF Exchange Example

Figure 4 describes the type of exchanges present in a typical engagement: 1. The edge service representing the system under test computes the Tx of the RF signal to detect/track the opposing system. 2. Using the core services provided by the IESM, the edge services call the common service to calculate propagation loss, weather effects, etc. 3. The common services provide the resultant Rx and RF signals to the edge service representing the opposing system. 4. The skin reflection from the opposing system is computed by the common service but the resulting track is evaluated at the appropriate edge service. 5. The resulting signals are modified accordingly by the common services and the results are exchanged with the SUT. 6. The SUT receives the modified signals and computes the detection/tracking characteristics for the SUT. 7. Based on the results, the SUT decides to apply EW means and invokes the common services to modify the emission accordingly. 8. The common service applies the appropriate effects/computations to the EW RF signal as it propagates through space. 9. The opposing system, via the common services, receives the modified EW signal and determines the effect of that signal on the system in the local appropriate edge service. 10. The opposing system, via the edge service, applies EW against the SUT and invokes common services. 11. The common services modify the EW signal to account for RF propagation, weather, etc. 12. The SUT receives the modified RF EW Signal via the common services and, through its services, determines the effect of the EW signal on the SUT.

Ideally, JSE would have the radar modelling characteristics for the generation and detection of an RF signal. Typically, a form of the radar range equation is modelled with additional considerations for processing choices or other unique aspects of the radar characteristics and resulting performance. JSE will utilize an RF environment to account for RF signal loss when propagated through space. Additional atmospheric parameters would include weather effects (moisture, etc.), Obscurants (smoke, etc.), and RF interference loss

from other RF energy propagating in the atmosphere. Receipt of the RF signal at the threat source would account for these losses and present RF parameters to the threat for RF signal detection and to present the necessary parameters to form an RF skin return (radar cross section) to support a detection calculation by the transmitting radar. Where these calculations actually occur in the JSE is a function of numerous considerations including the existing architecture of some of the system models, computational complexity, enterprise view of the desired long-term architecture, anticipated required fidelity, and impact to existing models and product lines within the community. The RF exchange example in figure 4 above will likely evolve as the IESM architecture matures.

The use of an executable architecture would allow the requirements team (as well as the V&V team) the ability to assess the completeness of the requirements necessary to support the modelling, simulation, and analysis objectives. Additionally, the executable architecture provides a coarse check on the modelling and simulation environment by comparing information-exchanges via use-cases. The executable architecture documents the requirement while providing a means to dynamically assess the execution of the information through the interfaces. Results from the execution of the simulation verify that the exchanges are properly documented in the architecture tool as part of the Operational and/or Developmental V&V activities conducted prior to testing.

4.3 Desired Features of an Executable Architecture

JSE will use commercially available executable architecture tools to support the development activity such as Enterprise Architect, Magic Draw and other SYSML/UML capable tools. The Air Force's intent is to describe the message interactions within the JSE by spectrum/band (RF, IR, Visual) as they relate to the various IESM Services (Core, Common, Edge, Exercise). These interactions will be developed and documented in the tools and then verified and validated against flight test, hardware in the loop (HITL), or anechoic chamber data as those components are developed and/or integrated and tested. From a prioritization perspective, Region "A" will take precedence over Regions "B" and "C." The use of executable architecture tools provides a means of developing, documenting, and testing not only the information exchanges, but the collection of information exchanges and corresponding required Quality of Service (QoS) necessary to populate the ICDs for the simulation. Reuse of the ICD's allows other Programs within the Air Force, other services, and partners to design their simulations against the ICDs and ensure interoperability with the JSE.

JSE also requires features tailored for the unique aspects of the architecture including the ability to link and track requirements based upon characteristics and features defined in the IESM. As previously described, the IESM decomposes the Information Broker into four service classes: Core, Common, Edge, and Exercise.

Recapping the previously described services, the core services are essential to all services and entities, are intricately linked, provide basic information broker functionality such as timing, routing, object declaration, object management, security, etc. Common Services ensure a fair fight and include RF, IR, Weather, Weapons, etc. Edge services provide functionality required by the JSE to support mission execution such as system representations, or unique components within the environment, etc. Finally, exercise services allow the user to define, configure, execute, and analyse the results from the environment. Exercise services would include mission planning, environment composition, orchestration, execution, and analysis.

Returning to Figure 4, and the information exchange example, the colors in the figure illustrate the various services involved in supporting an information exchange. In this example, timing, not shown in the figure, could readily be added in the form of quality of service (QOS) requirements. As written, the fighter aircraft shown within the figure are Edge Services and provide necessary war-fighting functionality to the test event. Common Services, represented in Black, illustrate the universal components required by all players within the environment to ensure a "fair fight". Common representations of universal services prevent inconsistencies in the representation of these services by establishing a single service to meet all entity needs.

The Violet color represents the routing paths required within the JSE for message exchanges and are Core Services. Core Services provide a variety of services as well as routing via information paths necessary to support Quality-Of-Service timing requirements. Conducting a complete test as illustrated in Figure 4 would be an example of an Exercise Service.

The ability to analyze not only the information exchanges, but also the Quality of Service required and provided within the executable architecture is an example of a custom requirement that the AF seeks within executable architecture tools. The Air Force intends to continue to drive the development of these tools to ensure the JSE needs are met while advancing its ability to rapidly characterize the performance of the environment in supporting Verification and Validation requirements for Test and Training.

5.0 DISCUSSION AND SUMMARY

The decision by test community leadership within the USAF and USN provides the community with an opportunity to advance the state-of-the-art in the design, integration, and application of a Virtual-Constructive real-time environment for test and training purposes. The leadership recognizes the limitations in today's physical test ranges in supporting current and future testing requirements in an environment that continues to expand its reliance on advanced sensors, datalinks, automation, and other technologies that do not readily lend themselves to live open-air-range testing. This recognition provides an opportunity to leverage significant investment already made in advancing Modelling and Simulation capabilities developing new capabilities only as required to meet Test and Training objectives. This risk-balanced approach avoids the pitfalls of many previous attempts to leverage Modelling and Simulation technologies by forming a composable environment that relies on proven technologies and established capabilities as opposed to constructing a complete a new environment fraught with development and cost risks.

JSE provides sharp contrast with previous efforts in another manner. JSE is a teaming activity leveraging the community investment in the JSE while accommodating individual service needs via a composable government-owned architecture and associated environment. The broader JSE Team provides a means to work across military service boundaries via that common architecture while allowing the military services to tailor the edge or exercise services as required. The core and common service are consistent and in fact, many of the edge and exercises services may remain consistent across the military services, but the key is that they do not have to do so. The military service partners have the inherent flexibility built into the architecture to tailor the architecture components depending upon their unique requirements and/or applications.

This paper has touched the basic tenants of the JSE. A complimentary paper by Dr. Andreas Tolk, the MITRE Corporation, provides an overview of the heart of the JSE, namely, the Information Exchange Services Matrix (or IESM). The IESM provides necessary services to the JSE allowing the various components within the JSE to function seamlessly with the ultimate objective of a complete integrated battlespace for Test and Training. [4] While the JSE today utilizes, the Global Reference Information Directory or GRID, the next generation of JSE development will expand the GRID to become the IESM.

In conclusion, the objective of this paper is to both produce knowledge for the reader and to solicit new ideas from the community to continue to advance modelling and simulation state-of-the-art for test and training applications by collaborating with our NATO Allies.

6.0 ACKNOWLEDGEMENTS

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Integrated Analysis in a Synthetic Battle Space Lessons from JPOW 2019

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ABSTRACT

This paper describes the collaborative R&D effort that has been conducted to develop and implement, for the first time in its history, an integrated analysis concept in the Joint Project Optic Windmill (JPOW) exercise series. Since the first edition in 1996, JPOW provides an extensive synthetic battle space - suitable for live-virtual-constructive participation - in which NATO and its coalition partners focus on enhancing interoperability in the Integrated Air & Missile Defence (IAMD) domain by exploring, testing and training future IAMD concepts and solutions.

The work presented is a joint effort of TNO Defence, Safety & Security, the Royal Netherlands Armed Forces, the German Air Force, and JPOW participants. This paper elaborates on the iterative and multi-disciplinary development and use of several state-of-the art data collection, monitoring, analysis, and visualisation tools enabling both in-situ/real-time data and performance analysis, as well as 'deep analysis' in a post-exercise analysis environment such as the Dutch IAMD Battle Lab. In addition, the organisational innovation that is required to successfully implement an integrated analysis concept will be highlighted. Based on lessons which were identified from JPOW19, this paper concludes by depicting the way ahead on how integrated analysis can enhance the effectiveness of synthetic battle spaces for both current and future military operations.

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Linda van der Ham has been working at TNO since 2012, after obtaining a MSc in Aerospace Engineering. As analyst in the field of Air & Missile Defence, she focusses on the evaluation of operational effectiveness of current and future systems, and operating concepts. In support of this work, Linda specialises in innovative methods of simulation and data analysis. She has been involved in the Joint Project Optic Windmill (JPOW) exercise series since 2013, for Concept Development & Experimentation (CD&E), scenario development, and in 2019 as lead of the concept development for integrated analysis and as core team member in the newly implemented Integrated Analysis Cell.

Lesley Jacobs joined TNO in 2001. As senior scientist, she is specialised in the fields of Military Operations Research, Training and Simulation. Her expertise is often called upon in military exercises, such as JPOW, and various Battle Labs. For JPOW19, Lesley was the lead for the R&D support provided by a multidisciplinary team of 25 TNO experts. In addition, she was a core team member of the Analysis & Assessment Control Group (AACG) and Joint Analysis Team (JAT) of JPOW19. Lesley obtained a MSc in applied educational science and technology, with a specialisation in simulation from Twente University in the Netherlands.

Hester Vermeiden has been working as analyst at TNO's Military Operations department since 2016, after having obtained her MSc in Aerospace Engineering. She is frequently involved in supporting the Royal Netherlands Armed Forces in experiments, exercises and tests, predominantly in the area of technical interoperability with Tactical Data Links. During JPOW19, she was a core team member of the newly introduced Integrated Analysis Cell supporting the Joint Analysis Team (JAT). Being certified in the NATO Lessons Learned methodology, JAT efforts were aligned accordingly.

Major Alexander Mac Lennan joined the Royal Netherlands Air Force in 1997. After graduation from the Royal Military Academy he started a career as Patriot weapon systems officer. Since 2015, Major Mac Lennan is chief of the CD&E Branch at the Knowledge Centre for Air & Missile Defence at the Netherlands Ground Based Air Defence Command (NLD GBADC). He is expert in Integrated Air & Missile Defence (IAMD), Theatre Missile Defence (TMD) and Missile Defence (MD), and a frequently invited guest lecturer. Since 2016, Major Mac Lennan has coordinated as JPOW project officer, the preparation and execution of the JPOW17 and JPOW19 editions. He is also the lead for the Dutch IAMD Battle Lab, and co-founder of the integrated analysis concepts described in this paper.

Lt.Col. Dirk Reinartz, joined the German Air Force in 1984. After graduating the Air Force Officer School in 1984/85, and Bundeswehr University Hamburg 1985-89, he became HAWK, ROLAND and PATRIOT weapon system officer/staff officer on unit and staff level, and CD&E consultant in the former Air Force Transformation Center. Since 2010, he is PATRIOT team leader in the SAM Weapons Assistance Team (System Integration and Checkout -SICO-Team), supporting the German PATRIOT armament organisation. For the JPOW19 edition, Lt.Col. Reinartz was chairman of the AACG & JAT. In addition, he took the organisational lead for introducing and testing the proof of concept for integrated analysis.

1.0 INTRODUCTION

The aim of the NMSG 2019 conference - *Towards the Next Generation Synthetic Battle Space* - is to identify how Modelling & Simulation (M&S) systems need to be modernised in order to represent the complex and contested future military operating environment and effects. This paper contributes to this aim by describing the collaborative R&D effort that has been conducted to develop and implement, for the first time in its history, an *Integrated Analysis Concept* in the Joint Project Optic Windmill (JPOW) exercise series [1].

Since its first edition in 1996, JPOW provides an extensive multinational synthetic battle space in which (NATO) coalition partners focus on enhancing interoperability in the Integrated Air & Missile Defence (IAMD) domain by exploring, testing, and training future concepts and solutions. An important feature of this synthetic battle space is that it is set up for enabling the participation of live/real platforms, systems and operational capabilities as well as virtual and constructive ‘simulated’ players. Therefore, an ongoing challenge is how to align interoperability and standardisation in architecture, set-up, and technical solutions between the M&S and the physical domain. The latter consisting of high-value, high-risk, and high-cost platforms, systems, and Command and Control (C2) capabilities with a considerable span of lifetime, and which comprise of both legacy systems and technologies as well as high-tech, state-of-the-art, and futuristic capabilities. This calls for both modernisation in the M&S domain, as well as finding appropriate solutions for being backward compatible with legacy systems and simulations in terms of interoperability standardisation. For JPOW, from a synthetic battle space design and development perspective, the three most important ones are - the ongoing need for developments in - the Distributed Interactive Simulation (DIS) protocol [2], the High Level Architecture (HLA) standard [3], and Tactical Data Links (TDLs), [4].

1.1 The need for next generation synthetic battle spaces

The need for synthetic battle spaces has been identified in various M&S communities for quite some time. For example, in 1995, a M&S vision statement of the United States Air Force highlighted the need for a Joint Synthetic Battlespace (JSB), i.e. ‘*an environment in which war fighters can train using real-world equipment, whilst being “virtually” immersed in a realistic contingency or wartime environment*’. In support of this vision, the need for military information processes to be more predictive, enabling commanders at the strategic, operational and tactical levels to anticipate rather than react was also identified. This is also referred to as Predictive Battlespace Awareness (PBA), [5]. The JSB strives to support training, acquisition, test and evaluation, and R&D [6]. To accomplish this, it operates at many levels of detail, including the engineering/technological level, entity level, mission level, operational level, and strategic level [7]. This is also seen in similar synthetic battle space initiatives, such as First WAVE [8], Collective Mission Simulation [9], Mission Training Through Distributed Simulation (MTDS) [10], and in The Netherlands: the IAMD Battle Lab [11], the Maritime Battle Lab [12], CABL [13], and the Simulation Battle Lab [14]. Such a broad scope makes it impractical and too costly to build all new simulation components. Synthetic battle spaces therefore often rely on existing components as much as possible. Hence, integrating legacy simulations and systems is seen as one of the most critical issues. By developing an Integration Framework (IF) this critical issue can be addressed. Such frameworks will reduce the effort required for large-scale simulation integration by an order of magnitude, and the construction of complex test beds, experiments, and exercises can be done with substantial less risk, time, and cost [7].

1.2 The need for next generation synthetic battle spaces in IAMD

Missile defence [15] plays a key role in minimising the threat of ballistic and cruise missiles to NATO and its deployed forces. Ballistic missiles present a problem from their destructive potential not only from a military aspect but also from a political aspect due to their potential as a terror weapon towards population centres and debarkation points. In parallel to the threat posed by ballistic missiles, there is an evolving threat posed by air breathing threats such as cruise missiles. Countering these threats is a combined and joint

endeavour, and calls for extensive IAMD exercise opportunities, such as JPOW, amongst coalition partners [16].

Within the IAMD domain there are many additional forces driving the need for advancing synthetic battle spaces, in particular in the areas of operations analysis (OA) and technical analysis (TA). Examples are the ongoing proliferation of missile threat and technologies, the introduction of new platforms, sensors, and shooter capabilities, coalition Force Threat Evaluation and Weapon Assignment (FTEWA) capability developments [17] via initiatives such as the Maritime Theatre Missile Defence (MTMD) Forum [18], and the Allied Partners M&S initiative, which also aim at advancing the level of solutions for M&S, OA, TA, and data exchange amongst coalition partners.

1.3 The IAMD Battle Lab - a persistent next generation synthetic battle space

With the aforementioned activities in mind, both the potential of and the need for developing synthetic or virtual battle spaces through specific battle labs within the Royal Netherlands Armed Forces was recognised, and has led to the foundation of various battle labs. In general, there is a wide variety and diversity in battle labs. Battle labs can be set up to explore a specific topic for a limited period of time, e.g. for a specific capability development within a specific domain or can be setup as a multi-purpose exploration capability with an unlimited life span across domains and capability developments. Common denominators are that they offer a synthetic battle space tailored for exploration, experimentation, and testing, usually with flexible and scalable means - with varying subject matter experts, hardware, software, models, simulations, IT infrastructure, processes, guidelines, and knowledge - to be able to analyse and assess effects and/or a chain of effects in a certain battle space. These effects can be caused by change in the military domain, both internal and external, and can be of different nature, such as changes in doctrine & tactics, equipment, technology, organisation, threats or changes in the (operating) environment [12].

The mission of the IAMD Battle Lab (BL) of the Netherlands Ground Based Air Defence Command (NLD GBADC) is ‘to offer a unique operations analysis, experimentation, test and exercise capability by which risks for current and future IAMD operations are reduced and the effectiveness of operational deployments of the Royal Netherlands Armed Forces is enhanced’ [11]. The main tasks and responsibilities of the IAMD BL are to:

- Conduct operations and technical analysis, for e.g. defence design plans, TDLs, live firings, mission rehearsal (in preparation of actual deployments), and mission support;
- Support doctrine and tactics development;
- Perform concept development & experimentation (CD&E), [19];
- Conduct interoperability tests with coalition partners and national IAMD units/assets;
- Perform operational test & evaluation (OT&E) in support of weapon system upgrades and/or introduction of new platforms in the Dutch Ministry of Defence; and
- Support IAMD exercises, such as Constructive Optic Windmill and Joint Project Optic Windmill.

1.4 JPOW an ad-hoc next generation synthetic battle space

Over the past decades, JPOW has become a leading IAMD exercise, where an important focus is on experimenting with novel air and missile defence concepts, new tactics, techniques and procedures (TTPs), and testing future capabilities in a multinational live, virtual, and constructive (LVC) environment. In 2017, the Royal Netherlands Chief of Defence (CHOD) tasked the Royal Netherlands Army and the NLD GBADC to organise the fourteenth edition of JPOW together with the German Air Force via a binational core planning effort, supported by the participating nations - Denmark, Finland, France, Germany, Greece, Norway, Spain, USA, and the Netherlands - and agencies, such as the Competence Centre for Surface Based

Air & Missile Defence (CCSBAMD), the Missile Defense Agency (MDA) of the United States of America, the Warrior Preparation Center (WPC) of the United States Air Force, the NATO Communication and Information Agency (NCIA), and the Joint Air Power Centre of Competence (JAPCC).

JPOW19 was executed via CFBLNet [20] at five locations in The Netherlands, Denmark, Germany, and the United States of America, from the 1st until the 30th of March 2019, with over a thousand participants. The exercise combined weapon system simulations with a command post exercise, supported by distributed interactive simulation with both distributed and co-located participants. The simulation architecture combined the integration of live, virtual, and constructive simulation models. Standardised tactical communications combined secure voice and data links. Shared command and control networks made up the command control, and communications structure.

JPOW19 addressed the need for close cooperation among participating nations and organisations during IAMD operations with emphasis on mission planning, mission execution and interoperability. The exercise did not only address the current and near term ballistic missile threat, it also focused on unmanned aerial vehicles and conventional manned air threats. All functional areas of NATO IAMD were incorporated in the exercise design, i.e. Surveillance, Battle Management Command, Control, Communications, and Intelligence (BMC3I), Active Air & Missile Defence, and Passive Air & Missile Defence. Finally, JPOW19 provided an opportunity to assess IAMD TTPs.

1.5 Paper overview

The work presented in this paper is a joint effort of The Netherlands Organisation for applied Science & Technology (TNO), the Royal Netherlands Armed Forces, the German Air Force, and JPOW participants. The remainder of this paper will elaborate on the iterative and multidisciplinary development and use of several state-of-the art data collection, monitoring, analysis, and visualisation tools enabling both in-situ/real-time data and performance analysis, as well as deep analysis in a post-exercise analysis environment such as the IAMD BL at the NLD GBADC. In addition, the organisational innovation required to successfully implement an Integrated Analysis Concept will be discussed. Finally, the way ahead will be described, on how integrated analysis can enhance the effectiveness of synthetic battle spaces for both current and future military operations, based on lessons from JPOW19.

2.0 TOWARDS INTEGRATED ANALYSIS

Before detailing how integrated analysis for synthetic battle spaces in the IAMD domain can be defined, it is worthwhile to take notice of how analysis can be defined and how in several other domains integrated analysis has been defined.

NATO's Joint Analysis Handbook [21] gives the following definition of analysis, i.e. *'the study of a whole by examining its parts and their interactions'*. The value of analysis is not to just develop findings, it is about developing findings with proof. As such, root-cause analysis is often referred to as key methodology. Analysis has to do with breaking down, dissecting, examining and/or reasoning. It is not about determining a value or rating. However, it can be initiated by an evaluation to determine what led to the eventual result. It is important to note that in this context, analysis is not the same as evaluation.

Within the United States National Oceanic and Atmospheric Administration integrated analysis refers to stock assessment methodologies that attempt to *'integrate multiple sources of data into a single estimation framework'*. Integrated assessment in this domain attempts to fit observations based on model predictions such as total landings by a fishing fleet, size samples of landings, standardised catch per unit effort by fleet, fishery-independent surveys, and tagging records on movement, growth, and recoveries [22].

Within the trading community, integrated analysis is seen as a means to regain an edge for trading, ‘*an integrated approach means fusing all the beneficial elements of fundamental studies, technical analysis and consensus figures into one immensely powerful blend of comprehensive and thorough analysis*’.

Due to recent innovations in technology, allowing the rapid assessment of large volumes of data, integrated analysis has become a viable tool for retail traders. Qualifying stocks that meet specific and tested criteria from precomputed lists can be collated and cross-referenced to produce advanced shortlists for further analysis. However, how is such an integrated analysis approach actually beneficial to a trader? Conceptually, a trader is faced with an intellectual challenge every time (s)he prepares to open or close a position. That challenge can be viewed as a problem which requires some form of solution. With integrated analysis, the philosophy for solution is to consider as many perspectives (or angles) as possible, before committing money to the market. The trader is aiming to only choose trades which meet multiple criteria [23].

According to the Psychological Methods Journal, integrative data analysis refers to ‘*the simultaneous analysis of multiple data sets*’. The main focus is on handling multiple types of data and having the ability to synthesise data into useful and timely information types [24]. The focus on synthesis and meta-analysis is particularly worthwhile to note for the IAMD domain. According to the field of Socially Responsible Investments (SRI) integrated analysis is a strategy in which analysis of environmental, social and economic issues contributes to better financial analysis by identifying additional sources of risk and opportunity, thereby contributing to better overall investment decision-making [25].

The four examples above highlight four different approaches on how to benefit from integrated analysis. Although differences in application can be noted, fundamental similarities can also be observed. For synthetic battle spaces, the main requirements for an integrated analysis concept are: the ability to handle large amounts of different types of data, the ability to monitor and analyse (near) real-time as well as having the ability to perform post-event (off-line) analysis, the ability to compare observations against (M&S) predictions, the ability to assess solutions against multiple criteria, the ability to synthesise and/or perform a meta-analysis, the ability to support decision making, and last but not least the ability to support (organisational) learning.

2.1 The need for integrated analysis at JPOW

At the After Action Review (AAR) Conference of JPOW17, which preceded the Concept Development Conference for the JPOW19 edition, the need for a more profound and timely (near) real-time analysis process and means during execution as well as the need for more profound post-exercise analysis options were identified by various stakeholders [26]. This has led to the definition, design, implementation, and first operational test & evaluation of an Integrated Analysis Concept during JPOW19, which also supported a so-called deep analysis effort in the post-exercise phase, with novel analysis tools, methods and techniques. Deep analysis is described in more detail in Section 3.3. After JPOW, these solutions have been transferred to the IAMD BL of the NLD GBADC in support of future JPOW editions and other BL events.

2.2 The role of a Joint Analysis Team at JPOW

The organisation and execution of the JPOW exercise series has mainly been set up in accordance with the BISC75-3 guidelines for NATO exercises [27]. Eight control groups were responsible for the preparation, execution, evaluation of JPOW19, and eventual transfer of main lessons to the JPOW21 edition. These are: the Exercise Control Group (ECG), the Concept Development & Experimentation Control Group (CDECG), the Scenario, Intel & Simulation Control Group (SISCG), the Operations Control Group (OCG), the Interoperability Control Group (ICG), the Information Management Control Group (IMCG), and the Analysis and Assessment Control Group (AACG).

Although monitoring and analysis is done at multiple nodes in the Exercise Control (EXCON) organisation as well by participating units/entities themselves, the AACG took the lead in coordinating and integrating analysis efforts for JPOW19, with a special focus on advancing the monitoring and analysis toolset for the EXCON organisation. During the execution phase the AACG transformed into a Joint Analysis Team (JAT). Next to the twelve AACG core team members, seventy-five JAT members from participating units joined the JPOW19 JAT effort.

The mission of the JPOW's Joint Analysis Team (JAT) is to 'help participants improve their performance on all aspects of IAMD by facilitating data collection, analysis and assessment of this obtained data'. Baseline for the work of the JAT are the participant's objectives. Extraction of metrics from these objectives was done, whenever possible. However, when metrics could not be extracted a general assessment of mission performance was made [28].

Objectives are key to the scenario design, (dynamic) scenario management during execution, as well as the analysis and assessment effort. By providing objectives, participating units/entities specify the requirements which the scenarios have to meet. In other words, objectives shape both CD&E and mission execution phase, as well as the analysis and assessment effort, leading up to a Lessons Identified Action List (LIAL) for both exercise organisation and participants. Objectives are intended end-results, to be accomplished by a JPOW unit/entity. They should be expressed in terms of desired behaviour or skill level, conditions under which it has to occur, and benchmarks against which it will be assessed [29].

Figure 1 presents the generic joint analysis and assessment loop for JPOW. Please note the difference between a Lesson Identified (LI) and a Lesson Learned (LL). Although the latter is always the aim, the accomplishment of LLs is a shared responsibility of all those involved [29]. For JPOW the actual achievement of a LL often is to be realised in the post-exercise phase or next JPOW edition [28].

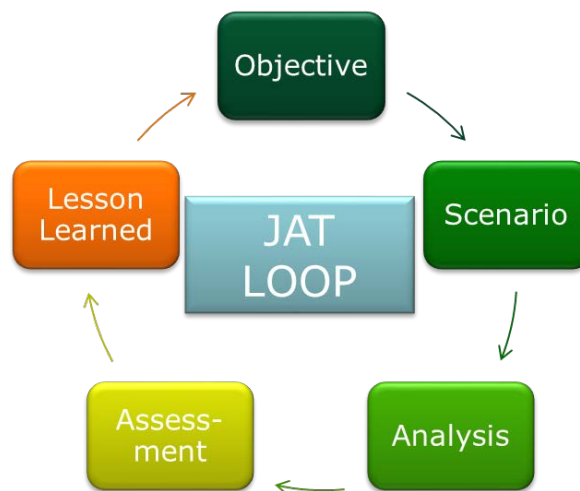


Figure 1: Joint Analysis & Assessment Loop [28]

In support of its joint analysis and assessment tasking, the AACG is responsible for developing a Data Collection and Assessment Plan (DCAP) [28]. Besides describing the data collection, analysis and assessment effort, this plan also describes the roles and responsibilities for the JAT organisation. The DCAP identifies the exercise and unit objectives to be assessed and the types of data to be collected, such as, deficits and shortcomings of organisational matters, doctrine, procedures, interoperability and other relevant fields of interest. The DCAP also provided participants with a template for structuring their objectives. The objectives template included fields such as: an overall objective description, measures of effectiveness

(MOEs), measures of performance (MOPs), scenario and/or exercise conditions, and data collection requirements. MOEs focus on achieving the overall mission and execution of assigned tasks. MOPs are measurable/observable breakdowns of a specific MOE, are more detailed, and provide a quantitative and/or qualitative baseline to be met by a force/unit [28].

The JPOW JAT effort clearly supports an objectives-based data collection, monitoring and analysis effort. However, it requires substantial effort and skill by all those involved. In addition, from a daily exercise point of view, time is always lacking for in-depth and yet timely monitoring and analysis process, in support of the daily learning processes. This outlines, in addition to the AAR results as described in section 2.2, the need for advancing the joint analysis and assessment efforts in JPOW.

3.0 Integrated analysis approach for JPOW

Part of the AACG/JAT role in the JPOW EXCON organisation was previously known as adjudication¹ and was limited to the assessment of engagement results. It was expanded for JPOW19 into an Integrated Analysis Concept to develop a more thorough understanding of the actions of the participating units, and to not only focus on the result of these actions. The main objective was to increase the training value of the exercise on a tactical and operational level by increasing the level of organisational learning for the JPOW EXCON organisation, its control groups, and participating IAMD units/entities.

In addition to the objectives-based analysis approach as summarised in the previous section, for the first time in JPOW, a data driven analysis effort was implemented and tested by using new methods, tools, and technologies. This also led to the set-up of an Integrated Analysis Cell in the JPOW19 EXCON organisation, which could now focus not only on the analysis of ‘what’ happened but also dive into the analysis of ‘why’ something happened during a specific scenario event. The data driven approach relies on synthesis of logged data and a comprehensive view on the data, such that in addition to the analysis of issues related to individual participants’ objectives also lessons can be identified on a joint level, e.g. within a certain operational area of interest such as active defence, passive defence or joint defence against air breathing threats and ballistic missiles. All logged data was stored in a central database, in which analysts could submit different (near real-time) queries to integrate data and investigate certain events more quickly, more detailed and in a more comprehensive manner.

3.1 Alignment with NATO LL processes

In support of the integrated analysis design for JPOW19, NATO’s Lessons Learned (LL) Staff Officers Course was attended by three JAT core team members. This was done to align the JPOW JAT loop and LL processes of the JPOW organisation, its control groups, and participating units/entities with NATO’s LL processes, methods and techniques [29]. The LL processes are in fact a continuous application of the OODA loop:

- Observe → determine the analysis requirement;
- Orient → describe causes of observed effects, impact, and relationships (analysis);
- Decide → determine Course of Actions (COAs), appropriate action(s) is/are chosen, and an action body is appointed for each Lesson Identified (LI) in the Lessons Identified Action List (LIAL);
- Act → appointed action body executes the action(s) to ensure that a LI transfers into a LL.

¹ Adjudication is originally a legal term, and refers to making a formal decision (judgement) after having reviewed arguments and evidence. This way it is also used in wargaming, where it refers to the procedure to impartially resolve the outcome of interactions between sides in a game [30]. In previous JPOW exercises, the task of the adjudication cell was mainly to decide when a unit was taken out by a threat and should be given a ‘time-out’ in the exercise.

The three key elements of a LL Capability are: structure, process, and tools. This means that having skilled and adequate LL personnel (for JPOW these are mainly the JAT members), a common LL process (i.e. the JPOW DCAP), and tools to support collection, storage, staffing and sharing of LL information, are essential. The desire to learn from others as well as to share own learnings has to be supported by effective leadership with timely and effective decision making, putting emphasis on the value of a LL capability, and creating an open learning environment. Critical success factors for any LL Capability are: leadership, mindset, information sharing, and stakeholder investment [29]. In JPOW these responsibilities are bestowed mainly upon the leadership of the AACG.

3.2 Objectives-based and data driven analysis

An integrated analysis concept has to take into account all aspects which play a role in the course of an exercise, experiment and test, such as the objectives, scenarios, vignettes, simulation, connectivity, tactical data links, tactics and procedures. This also calls for the integration of data, knowledge and analysis efforts from different control groups, participating units and JAT observers. For JPOW19, this was done according to the framework as shown in Figure 2.

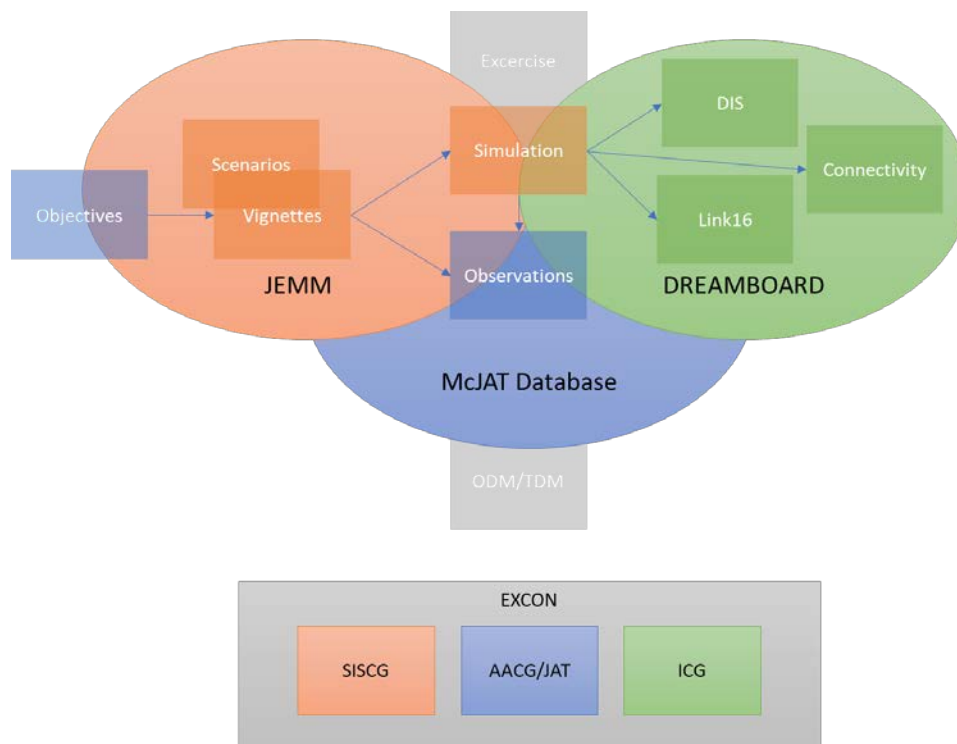


Figure 2: Objectives-based & data driven analysis approach

Monitoring and analysis was performed at various nodes in the EXCON organisation. Via the introduction of new tools, such as JEMM and McJAT, an objectives-based data analysis approach (typically focussing on the analysis of qualitative data provided by the objectives, scenarios, vignettes, and JAT observations) could be combined with a data driven data collection, monitoring, and analysis approach provided by a DREAMBOARD database, an analysis application and various dashboards, in addition to other analysis tools already available in the EXCON organisation. The latter approach typically focusses on the analysis of quantitative data available via the DIS and TDL network, as well as the connectivity status of all participants. More information on these tools is provided in section 4.2.

Figure 3 gives a functional overview of the integrated analysis effort for JPOW19, starting with pre-JPOW activities such as defining the DCAP (process), giving training to all JAT members via JAT academics (structure), and the development of an integrated analysis concept based on toolset of already existing and new tools (see section 4.2). The figure zooms in mainly at the daily integrated analysis effort during the execution phase, also referred to as the in-situ or near-real time monitoring and analysis process. The main objective for this phase was to support and enhance the quality of the Operational Debrief Meeting (ODM) and the Tactical Debrief Meeting (TDM) by improving the quality, speed and integration of all available data via new tools and methods into an integrated analysis effort. Please note that in JPOW19, due to the high number of participants, two parallel daily debrief sessions were conducted in support of the operational and tactical IAMD levels.

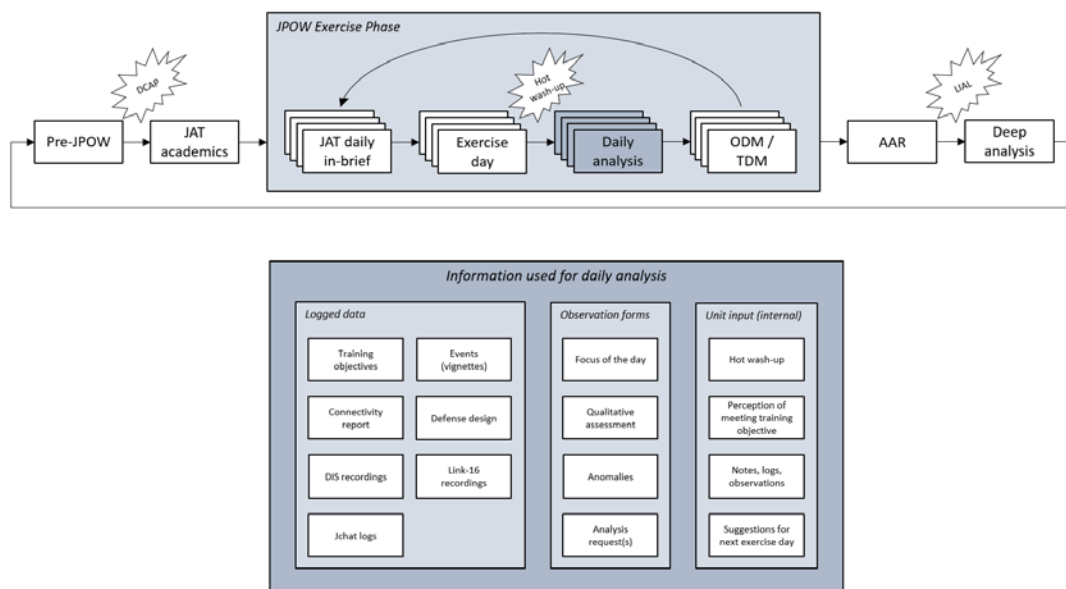


Figure 3: Integrated Analysis for JPOW19

The JPOW execution phase ended with a plenary After Action Review (AAR) with approximately five hundred participants. Main lessons were captured in Intermediate Data Collection Sheets (IDCS), AAR reports, First Impression Reports (FIRs), LIALs, and the Final Exercise Report (FER). After JPOW19, a deep analysis effort was performed, which led to additional lessons identified for the JPOW21 edition.

3.3 Deep analysis

Deep Analysis is a term commonly used in the IAMD community for detailed analysis of a live firing event of, for example, a single missile in a certain C2 and sensor environment, based on a specific threat, and scenario. For JPOW, deep analysis has been defined as the part of the integrated analysis concept that provides a solid basis for a more thorough post-exercise analysis effort, both in terms of integrating operations analysis and technical analysis, and with a special focus on off-line and faster than real time analysis means.

In the aftermath of JPOW19, members of the AACG and ICG were able to perform operations and technical analyses at various nodes in Germany, The Netherlands, and the USA. To follow-up on this distributed analysis effort, a Technical Interchange Meeting (TIM) was organised by the ICG. The main topic for

analysis of this TIM was the degradation of the Common Operational Picture (COP) with issues such as misidentification and dual tracking of simulated objects which could detract from the situational awareness of the participants. Therefore, the joint analysis effort in this week-long TIM focussed on detecting interoperability issues based on a technical analysis of TDL and DIS data performance. In particular, the adherence to standards and reporting of tracks was carefully analysed. The post-exercise analysis report of the ICG serves as a first investigative assessment, while special reports with a LIAL for individual units are made to support their necessary preparations for the JPOW21 edition, and to improve the training value of the next JPOW edition from an interoperability perspective [31].

Examples of operations analysis in a post-execution phase that can be supported with the integrated analysis approach are the ability to assess the effectiveness of the planning of the overall IAMD mission, the execution of layered defence designs, and the investigation of joint operating issues, upon request by participants and the JPOW EXCON organisation. Participating units/entities can also perform their own specific deep analysis effort by analysing their performance based on, for example, root cause analysis of relevant exercise data which are available upon request.

4.0 INTEGRATED ANALYSIS METHOD AND TOOLING

In the preparation leading up to JPOW, participants provided objectives, such that the CD&E and exercise scenarios could be written to accommodate these. Most of the simulated events during the exercise, also referred to as vignettes, were therefore directly related to a (training) objective and were used to focus the analysis efforts. The Main Event List (MEL) contains these vignettes delineated in location and time, with an indication of the objectives from which they originated. To support the daily debriefs, a number of relevant vignettes were selected to be analysed thoroughly. This relation between objectives and scenario also helps to focus the attention of the JAT observers and their respective units.

The scenarios were recorded, allowing for replay faster than real-time without affecting the simulation environment. This was used during the daily in-brief for the JAT observers to give a global impression of the daily scenario as well as an indication of when specific events were scheduled to occur. It was also used to visually support the daily debriefs with replays of relevant occurrences. Apart from the pre-selected vignettes, other interesting situations might occur which would require attention in the daily debriefs. Upon request, re-runs of specific parts of the scenario could be done afterwards by filtering all simulation data in location and time.

4.1 Improving daily data collection

The data driven analysis approach relies on a variety of logged exercise data. For JPOW19 this consisted of: observation forms, DIS, Link-16, scenario descriptions (including MEL and shotplans), leaker charts, defence designs, communications logs, and questionnaires.

Daily *observation forms* provided a framework for qualitative assessments by the JAT observers. The forms were developed by the AACG and are based on the NATO LL format, describing: Observation, Discussion, Conclusion, and Recommendation (ODCR), [29]. All observations are related to a specific (training) objective, and provide the possibility to submit a request for a specific investigation/analysis by the Integrated Analysis Cell.

The *DIS 6.0* protocol was used to s(t)imulate all objects in the JPOW19 scenarios, and provided relevant data on the simulated performance of all LVC participants. For the next JPOW edition, an upgrade to the *DIS 7.0* protocol is needed, especially in support of interrogation of Identification of Friend or Foe (IFF) at Mode 5.

Link-16 was used as predominant TDL during JPOW19. Link-16 enables the communication of tactical

data between units/entities, mainly for common situational awareness, engagement coordination, and status reporting. In LVC exercises such as JPOW, constant monitoring and analysis in the EXCON organisation is required of both DIS and TDL network to be able to verify the ground truth (scenario delivered via DIS) with the perceived truth (via TDL). This subsequently enabled the Integrated Analysis Cell to answer specific participant questions with respect to their (joint) performance in a certain area. In the Integrated Analysis Cell, Link-16 analysis was focused more on operational aspects than on technical performance (connectivity) and participants' adherence to NATO standards and other data exchange agreements. This was monitored and analysed in the ICG.

The *scenario descriptions* contained vignettes, the MEL, shotplans, and threat definitions for DIS. They were captured in the script for the scenario stimulation tool PELORUS (see section 4.2). For JPOW19, the general storylines and MEL were made available in text via the scenario management tool JEMM (see section 4.2).

A so-called *leaker chart* helps to identify an (un)successful defence against ballistic missiles and to identify root causes, e.g. why a particular engagement was successful or not. As such, it provides a common Terms of Reference (TOR) for the analysts. For ballistic missiles such a reference chart was already available at previous JPOWs. At JPOW19, for the first time, it was also possible to assess the effectiveness of defence against air breathing threats (ABT), a far more complicated analysis requirement, based on a leaker chart. Also during JPOW19, possibilities for the automation of these leaker charts was looked into, which resulted in various dashboard views with desired statistics, and which might also become available as real-time status display in future exercise editions.

The *Defence Design* is the overall result of the IAMD mission planning process, which consist of multi-layered defence plans. It contains the defended areas and allocated positions of IAMD units in the scenario. It provides, next to the leaker charts, an important baseline or TOR for investigation and analysis

Communication logs consisted of chat, voice (sometimes), notes based on phone calls, written questions and responses. By correlating these type of data to anomalies detected in the DIS/L16 logs it was possible to pursue more in-depth investigation and analysis. This is due to the fact that decision making in complex warfare situations can evoke multiple courses of action that have to be investigated carefully via appropriate qualitative data analysis means, mainly focussing on why a certain decision was made by operators/units/C2 entities, and supported by more quantitative analysis means focussing on the outcome of such decision making and/or actual adherence to interoperability standards.

In addition to the daily data collection via observation forms, two *questionnaires* were sent out to the participants and control groups in support of the post-exercise analysis effort. These were an *Intermediate Data Collection Sheet (IDCS)*, which was released at the end of the CD&E phase, and an *AAR report template*, which was released at the end of the execution phase. The former contained the qualitative assessments on the final test & integration phase and the CD&E phase, including academics, Combat Enhancement Training and Force Integration Training (CET/FIT). The latter document focussed on collecting data on the mission execution phase and the planning conferences prior to the exercise. The analysis of the IDCS resulted in a LIAL, and the main lessons of the AARs were captured in the First Impression Report (FIR) of the AACG [32], and the JPOW19 Final Exercise Report (FER), [33].

4.2 Expanding the toolset

In support of the JPOW EXCON organisation, various M&S and analysis tools are brought together in support of scenario development, scenario management, enhancement of the scenario with constructive simulations, monitoring, visualisation, logging, replay and analysis of DIS and TDL performance. Similar to other ad-hoc synthetic battle spaces, JPOW's toolset is defined by a joint, international, scientific, industrial, and NATO toolset. For each JPOW edition, investigations are made to see if the EXCON toolset (still)

suffices or that areas of improvement are deemed necessary. Until the JPOW17 edition, the integrated use of these EXCON support tools for analysis was not foreseen.

In synthetic battle spaces with large amounts of data-exchange, it proves beneficial to have similar types of tools available. It ensures robustness and flexibility, and moreover it provides the ability to cross-reference results of a specific monitoring, investigation, and analysis process. This contributes substantially to the trustworthiness and validity of a joint analysis and assessment effort. The main tools for providing EXCON support in the JPOW exercise series are: PELORUS, JROADS, GRACE, JODA, GAMEBOARD, TDACS, and ADIVS. A brief summary of each tool (suite) is given below.

PELORUS is an extensive s(t)imulation suite developed by JESSIX for the US MDA [34]. It was procured by the Royal Netherlands Armed Forces in support of the delivery of synthetic battle spaces for the IAMD domain. With *PELORUS* it is possible to develop, test and run extensive LVC scenarios, and enhance these scenarios with both scripted and dynamic play of constructive entities, such as additional blue forces and red forces. In support of the JPOW execution phase additional manning support and a substantial set of extra *PELORUS* systems was provided by JESSIX to the EXCON organisation.

The *Joint Research on Air Defence Systems (JROADS)* tool suite [35], developed by TNO, offers an advanced, modular and flexible simulation environment in a wide range of military domains. *JROADS* models can be used at various levels of detail, such as running high-fidelity effectiveness analyses, supporting (inter) national exercises and experiments (CD&E), delivering testbed support, and running war games. For JPOW19, *JROADS* was used for various purposes. During the risk reduction tests prior to the exercise execution phase, it was used as test and analysis environment. During the actual exercise execution, *JROADS* was used to enable the:

- monitoring and analysis support in the EXCON organisation by TNO analysts in the ICG area;
- participation of two Air Defence and Command Frigates (ADCF) of the Royal Netherlands Navy via a mobile maritime battle lab set-up, which consisted of an integrated ADCF Combat Management System - *JROADS* - Linpro TDL solution; and
- participation of the Royal Netherlands Army with a *JROADS* Army Ground Based Air Defence System (AGBADS).

The *Generic Reconstruction And Computing Environment (GRACE)* is a tool suite developed by TNO and the Royal Netherlands Navy for reconstruction and analysis [36]. In *GRACE*, data from multiple sources, such as log files and live feeds, can be combined and synchronised in time, allowing analysis and (re)-play, for example, in 2D/3D visualisations, charts, graphs, timelines, and tables. During live exercises and/or live firings *GRACE* is used both for analysis on-board of naval vessels and for post-exercise/post-mission analysis at the Maritime Battle Lab of the Royal Netherlands Navy [12]. For JPOW19, *GRACE* was mainly used in the ICG area of the EXCON organisation as technical analysis tool.

JODA (Joint Operations Data Analysis) is the logging & replay application for *GRACE*. It can simultaneously record multiple network traffic streams, store it, or redistribute the data over a data bus. It can simultaneously replay live streams or recordings on the network again, with or without a delay. Timestamps in the replayed data can be updated, so the resulting data stream is effectively a live data stream. It is capable of handling various types of data, such as TDLs and DIS. In combination with analysis tooling, such as *GRACE* and *DREAMBOARD*, the recorded data can be inspected and visualised live, enabling the analysts to monitor and analyse an event directly.

GAMEBOARD provides a 2D visualisation of the synthetic battle space and was developed by TNO for, amongst others, NCIA's Integrated Test Bed [37]. *Gameboard* provides a complete overview of the simulation entities on the network, either as truth data provided by the threat generation tools, as perceived data in an operational context, or as a combination of both superimposed on a single viewer.

The *Tactical Data Analysis and Connectivity System (TDACS)* is developed by Märzen (USA) as a datalink management tool. It provides means for logging, visualising and analysis of Link-16 messages. For JPOW the BMD adjudication plugin was made available, which allowed for analysis of individual ballistic missile shotlines with all related detections, tracks and engagements [38]. The main use of TDACS in the JPOW EXCON organisation is aimed at technical monitoring and analysis of TDL performance, connectivity issues, and assessment of BMD engagements.

The *Air Defense Interoperability Validation System (ADIVS) II* is developed by Peraton (USA) for analysis and monitoring of TDLs. It is used by the German Armed Forces for real-time situational awareness during interoperability testing and training in air defence operations exercises [39]. AT JPOW, ADIVS was used mainly for technical monitoring and analysis purpose in the ICG area of the EXCON organisation.

In the aftermath of the JPOW17 edition, the need for integrated analysis, mainly focussing on the integration of technical and operations analysis on various levels and locations in the exercise, as well as the integration of analysis means for both Air Defence and Missile Defence (i.e. IAMD analysis) was identified. This led to the introduction of JEMM, McJAT, and DREAMBOARD. Via this approach, the JPOW organisation was able to leverage as much as possible on the proven value of existing tools and their unique capabilities, and at the same time enhance joint monitoring and analysis capabilities for the JPOW19 edition via an iterative development and test approach under guidance of the AACG/JAT. Based on the availability of the aforementioned tools, McJAT, JEMM, and DREAMBOARD were subsequently prepared, fielded and tested during JPOW19.

The *McJAT* database was developed by the German Air Force for data collection and data storage of qualitative assessments made by JAT observers and participants. McJAT is based on a MS Access database and the ODCR format of the observation forms as displayed in figure 4. These forms could be accessed via a dedicated JPOW19 SharePoint environment and were stored in the database. Prior to the JPOW execution phase, JAT members received training in how to support integrated data collection and analysis and how to work with all tools available. During JPOW19, various improvements on accessibility and usability of the McJAT database were made on the spot by the AACG, based upon direct feedback from JAT members and the IMCG.

Input Observations - SME -

Objective Number: DEU-001 Date planned: 3-1-2019
 Nation: DEU Unit / Entity: SAM Wing 1 Assessment Area: Active Defence

Name SME: Dell, Andreas Date Observation: 3-1-2019
 Location: SAMOC Time Observation: 1112

☐ Status Green ☐ Status Yellow ☒ Status Red

Obj. No	Date	Name SME
DEU-001	3-1-2019	Dell, Andreas
NLD-001	4-1-2019	
NLD-001	4-1-2019	
ESP-001	6-1-2019	Allen, Woody
FR-001	6-1-2019	
ITA-001	11-1-2019	
ITA-001		

Objective:

☒ Problem Areas Enter short description

Local Hand- or Software

Communication aspects

Coordination or C2

Crew or Operator

Abnormal procedures

Sim artificialities

Other reason

☒ Analysis requests

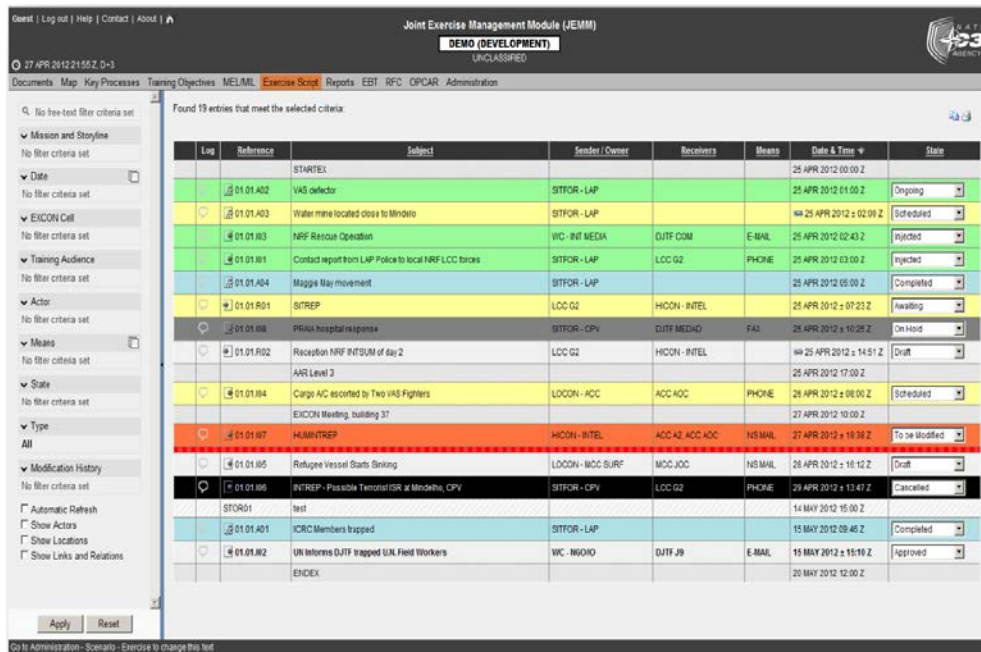
☒ Lesker overview ☐ Success of engagements ☐ Connectivity report ☐ Vignette or replays

Other requests

Objective Number: NLD-001 Date planned: 4-1-2019
 Nation: NLD Unit / Entity: ACBADS Assessment Area: BMC41

Figure 4: Overview of the McJAT database & ODCR format for entering observations

The *Joint Exercise Management Module (JEMM)*, displayed in figure 5, is a NATO tool developed by NCIA for the Joint Warfare Centre (JWC). It is currently in use by most of the NATO members to support their (inter)national exercises, such as VIKING and MSG-106 NETN. JEMM provides an integrated Exercise Management Environment to improve awareness in and provide control mechanisms to an EXCON organisation. It can be used as planning and management tool for scenario development and scripting, and contains scenario events and injects, based on storylines and participant objectives. For JPOW19, JEMM was used to a limited extent by the SISCOG for scenario development. During the exercise the use of JEMM was tested by the EXCON organisation and several participants for monitoring the overall execution and the play of non-simulated events, such as the intel scripts.



The screenshot shows the JEMM interface with a sidebar on the left containing filter options like Mission and Storyline, Date, EXCON Call, Training Audience, Actor, Means, State, Type, and Modification History. The main area displays a table of events with columns: Log, Reference, Subject, Sender / Owner, Receivers, Means, Date & Time, and State. The table lists various events such as 'STARTER', 'VMS detector', 'Water mine located close to Mindelo', 'NRP Rescue Operation', 'Contact report from LAP Police to local NRF LCC forces', 'Maggie May movement', 'STREP', 'PRGA hospital response', 'Reception NRP INFUM of day 2', 'ARR Level 3', 'Cargo AC escorted by Two VMS Fighters', 'EXCON Meeting, building 37', 'HUMANITREP', 'Refugee Vessel Starts Sinking', 'IN/REP - Possible Terrorist IIR at Mindelo, CPV', 'JCR Members trapped', 'UN informs DJTF trapped UN Field Workers', and 'ENDEX'.

Log	Reference	Subject	Sender / Owner	Receivers	Means	Date & Time	State
		STARTER				25 APR 2012 00:00 Z	
	01 01 A02	VMS detector	STFOR - LAP			25 APR 2012 01:00 Z	Ongoing
	01 01 A03	Water mine located close to Mindelo	STFOR - LAP			25 APR 2012 02:00 Z	Scheduled
	01 01 A03	NRP Rescue Operation	WIC - INT MEDIA	DJTF COM	E-MAIL	25 APR 2012 02:43 Z	Injected
	01 01 A01	Contact report from LAP Police to local NRF LCC forces	STFOR - LAP	LCC G2	PHONE	25 APR 2012 03:00 Z	Injected
	01 01 A04	Maggie May movement	STFOR - LAP			25 APR 2012 05:00 Z	Completed
	01 01 A01	STREP	LCC G2	HICOM - INTEL		25 APR 2012 07:23 Z	Awaiting
	01 01 A08	PRGA hospital response	STFOR - CPV	DJTF MEDAD	FAL	25 APR 2012 10:29 Z	On Hold
	01 01 A02	Reception NRP INFUM of day 2	LCC G2	HICOM - INTEL		25 APR 2012 14:51 Z	Draft
	01 01 A03	ARR Level 3				26 APR 2012 17:00 Z	
	01 01 A04	Cargo AC escorted by Two VMS Fighters	LOCOC - ACC	ACC ACC	PHONE	26 APR 2012 08:00 Z	Scheduled
	01 01 A07	EXCON Meeting, building 37				27 APR 2012 10:00 Z	
	01 01 A07	HUMANITREP	HICOM - INTEL	ACC A2 ACC ACC	NS MAIL	27 APR 2012 15:38 Z	To be Modified
	01 01 A05	Refugee Vessel Starts Sinking	LOCOC - WCC SURF	WCC JOC	NS MAIL	26 APR 2012 15:12 Z	Draft
	01 01 A06	IN/REP - Possible Terrorist IIR at Mindelo, CPV	STFOR - CPV	LCC G2	PHONE	26 APR 2012 13:47 Z	Cancelled
	STOR01	Test				14 MAY 2012 15:00 Z	
	01 01 A01	JCR Members trapped	STFOR - LAP			15 MAY 2012 09:40 Z	Completed
	01 01 A02	UN informs DJTF trapped UN Field Workers	WIC - NSOIO	DJTF J9	E-MAIL	15 MAY 2012 15:10 Z	Approved
		ENDEX				26 MAY 2012 12:00 Z	

Figure 5: Joint Exercise Management Module

The *Dashboard for Real-time Event Analysis & Monitoring (DREAMBOARD)* has been developed by TNO, in a multidisciplinary and iterative R&D effort, for synthetic battle spaces such as JPOW and the IAMD BL. The aim of this R&D effort was to provide new solutions for integrating the means for technical and operations analysis. During JPOW19, the goal was to both demonstrate and explore these solutions, in addition to (and making use of) the already existing means and tools such as GRACE and JODA. This was done by using advanced M&S, technical & operations analysis, and data-science methods and techniques.

DREAMBOARD's front-end consists of two types of widget-based client applications: a dashboard view and an analysis application. The dashboard view enhances monitoring and shared situational awareness at different nodes in the EXCON area. This view can be tailored to different needs and includes displays such as an issue tracker (in support of monitoring, investigation, and resolving issues found during execution), a status overview of players on the DIS network, and automated rule checks (such as for the identification of anomalies with respect to DIS protocol adherence). The analysis application can be used on various working stations for monitoring, querying, and analysing all logged data.

The back-end of DREAMBOARD's framework consists of a data logger, a database server and a display server. The data logger, that allows for integration with existing tools such as GRACE and JODA uses parallel data capture mechanisms to collect all DIS and Link-16 simulation and connectivity data, and processes these data for storage in the database. The database is a relational SQL database capable of storing

time-series data containing geographic objects. The display server acts as bridge between client views in the EXCON organisation and the database. It synchronises and distributes relevant information to the dashboard views (using automated rules for real-time monitoring) and processes queries from the analysis applications. Figure 4 gives an overview of the set-up at JPOW19.

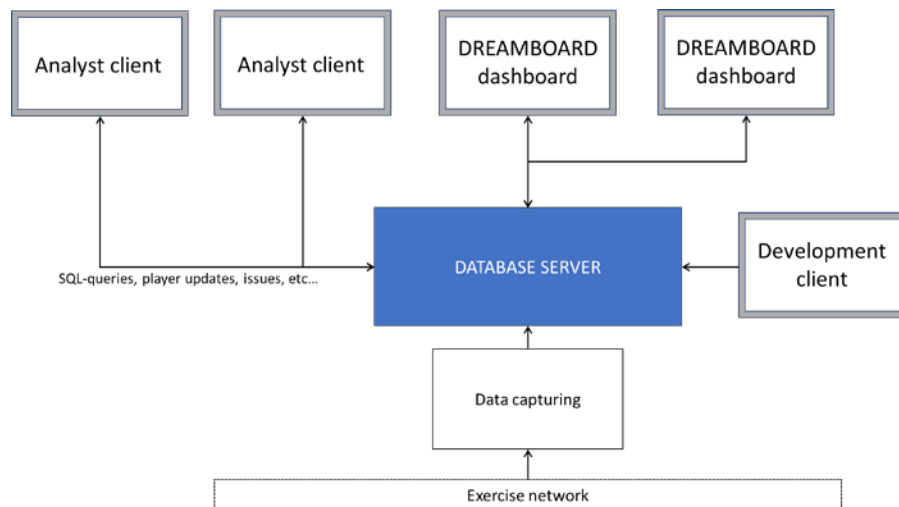


Figure 4: Set-up of DREAMBOARD at JPOW19

During JPOW19 execution, all DIS and Link-16 network traffic was logged using the DREAMBOARD database. Data that could not be recorded included voice communication and operator-system interactions (for example which buttons were clicked). The latter was due to the infrastructural set-up of the exercise. However, it is possible to enable logging these kinds of data in the future. Based on direct user feedback and user requests, additional features were developed onsite, even during the execution phase.

4.3 Extending the EXCON organisation

In support of the introduction of the Integrated Analysis Concept, the adjudication cell in the JPOW EXCON organisation was extended and transformed into an Integrated Analysis Cell. In this cell the analysts could work on dedicated DREAMBOARD analysis stations. In addition, various dashboard functions of DREAMBOARD were displayed at large mission monitoring screens to enhance shared situational awareness in the EXCON areas. To ensure that the analysts could focus on their analysis work, the monitoring of the scenario execution by other JAT-members was done at nearby working locations in the EXCON area. Requests for analysis could be done via multiple ways of communication such as phone, mail, chat, and request for analysis/observation forms. Managing and prioritising analysis requests was a shared tasking between several leads in the EXCON/JAT team. To ensure that stakeholders knew about the novel support offered by the Integrated Analysis Cell various briefings and trainings were given to stakeholders prior and during the JPOW19 execution. Last, but not least, the set-up and introduction of an Integrated Analysis Concept was strongly supported by the AACG lead, the JPOW19 Project Office, and the binational JPOW19 Core Planning Team.

5.0 MAIN RESULTS AND TAKE AWAYS

This paper described the need for advancing analysis methods, tools, and techniques in synthetic battle spaces for IAMD. Next, a first proof of concept for integrated analysis for the IAMD domain in general and for the JPOW exercise series in particular has been presented.

Main requirements for integrating analysis efforts in synthetic battle spaces are:

- the ability to handle large amounts of different types of data;
- the ability to monitor and analyse (near) real-time as well as having the ability to perform post-event (off-line) analysis;
- the ability to compare observations against (M&S) predictions;
- the ability to assess solutions against multiple criteria;
- the ability to synthesise and/or perform meta-analysis;
- the ability to support decision making; and last but not least
- the ability to support (organisational) learning.

The Integrated Analysis Concept that has been developed for JPOW19 required both organisational and technological innovations. In support of the organisational innovation, the organisation and methods of data collection, monitoring and analysis were advanced via the DCAP and led to the introduction of an Integrated Analysis Cell in the EXCON organisation, which could focus not only on the analysis of ‘what’ happened but also dive into the analysis of ‘why’ something happened during a specific event. The importance of training and familiarisation with new concepts and tools was highlighted in the feedback received from various stakeholders.

The technological innovations requiring the enhancement of integrated data collection, storage and analysis, were based on a variety of qualitative and quantitative data sources and tooling already in use. This led to the introduction of NATO’s JEMM tool in JPOW exercise series, the development of a McJaT database, and to strengthen the already existing monitoring and analysis means via the development of a DREAMBOARD database, an integrated analysis application, and various dashboards for enhancing shared situational awareness in the JPOW EXCON organisation.

Tools such as a MS Access database and SharePoint provide flexible solutions that are relatively easy to develop, manage, and alter during use. However, guaranteed data storage and accessibility of data is crucial for the trustworthiness of any data collection and data storage solution provided. For future JPOWs, the daily and highly time critical qualitative data collection process could be enhanced further by the introduction of electronic data collection tools supporting the JAT observers in their work at any location in the exercise. This calls for digital portable solutions that can be used both in a stand-alone operating mode (accredited for use in a NATO SECRET environment) and an upload/networked mode for entering data into the McJaT database.

The familiarisation with JEMM in the JPOW19 EXCON was well received. The main objective for this introduction in JPOW19 was to assess the potential and added value of such a tool suite in the EXCON area during the execution phase. JEMM was mainly used for monitoring the Main Event List/Main Incident List (MEL/MIL), and for keeping track of non-simulated injects in the scenario in support of the Intel Response Cell. The potential of using JEMM also during scenario development prior to execution was clearly identified by the SISCG, as well as the potential of having an interface between PELORUS and JEMM to be able to monitor the scripted simulated injects in the scenario via JEMM as well. Both lines for follow-on developments are currently pursued.

For the DREAMBOARD database, the JODA data capturing mechanisms proved to be very robust. Data capture and storage did not fail once during twenty days of consistent and extensive data logging. This was a crucial enabler and was essential for establishing trust. The ability to handle different types of data, as well as the ability to combine a time scaled (relational) database and a geographical database extension (for retrieving locations) ensured that at any time and location relevant data sets could be integrated for analysis. This was facilitated by automated rules, queries, and logic. Flexible, meaningful, and user-friendly

dashboards contributed to the shared situational awareness in the JPOW19 EXCON area. Ongoing developments, based on direct user feedback, were implemented during JPOW19.

The first proof of concept for integrated analysis as fielded and tested in JPOW19 has led to a flexible and robust set of capabilities, which were the combined result of using both existing and new tools, methods and techniques. Due to the highly collaborative and multidisciplinary R&D approach, based on advancements and the combination of novel M&S, technical & operations analysis, and data science methods and techniques, this could be done at relative low cost and low risk. Derived from this first experience, the list of new ideas and requirements to further analysis for synthetic battle spaces in the IAMD domain is quite substantial. To quote some participants on both potential and added value:

*‘via integrated analysis it is possible to translate zeros and ones into common operator language’ and
‘via such an approach the investigation, analysis, and common understanding of why certain events in the
scenarios played out in the way they did, can be done in a comprehensive manner’.*

After JPOW, the new analysis tools, methods, and data results have been transferred to the IAMD BL of the NLD GBADC in support of future JPOW editions and other BL events. For JPOW21, next to follow-on developments for the toolset, it is important to extend familiarisation and training on integrated analysis to all control groups. Also, the integration of technical and operational analysis can be strengthened further by rethinking the set-up of the Integrated Analysis Cell in the EXCON area.

6.0 WAY AHEAD

The reason why integrated analysis is probably such an appealing concept has likely to do with the fact that it supports the universal human need for sense making in any environment in which they have to operate. However, sense making is easily hampered when having to act and decide in complex mission environments dominated by large amounts of data, such as the battle spaces of the nearby future, in which all military domains - cyber, land, air, maritime, and space - have to be interoperable to deliver synchronised and mutually supporting effects in the human, physical (kinetic), and information dimension.

Integrated analysis will require ongoing developments in terms of (tailored) organisation, methods, tools and technologies to keep up with the high demands of this so called multi-domain-battle space, including military operations and warfares such as operations in contested urban environments (OCUE), littoral operations, and IAMD. This also strongly drives the demands for next generation synthetic battle spaces and their added value by supporting complex sense and decision making by thorough and comprehensive analysis means.

Similar to the challenges for assessing the validity and fitness-for-purpose of large scale simulation integrations, integrated analysis calls for a careful application of investigation, analysis and assessment methods on certain actions, events or anomalies that occur in these battle spaces. This should be done by cross-referencing both the method used and actual outcome (assessment) and is particularly relevant when it concerns a joint analysis and assessment effort. Whilst the orchestration of various analysis means and methods are key to success in joint synthetic battle spaces, this does not necessarily apply to the actual integration of all tools and their specific functions into one collective toolset. By using integration frameworks it is relatively easy to ensure that separate tools can operate together in an orchestrated manner.

From the first proof of concept as described in this paper, it is important to note that strong advancements can be made by using data driven analysis approaches, next to the more commonly used objectives-based data analysis approaches. In particular when combining (novel) M&S, operations & technical analyses, and data science methods & techniques. These findings were confirmed by a post-JPOW data challenge. A one-day hackathon for TNO data scientists, led to the development of novel analysis means and views on the data collected. It was impressive to see how without any domain knowledge, these data scientists were quickly

able to come up with novel solutions. In support of these findings, and in support of R&D efforts for joint synthetic battle spaces it is recommended that NATO STO pursues more integrated studies by combining MSG, SAS and HF knowledge and expertise.

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Navantia's Digital Twin Implementation Perspective in Military Naval Platform Life Cycle

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ABSTRACT

Digital transformation is a cornerstone to increase efficiency and productivity in today's businesses and enterprises, and Modelling and Simulation (M&S) play a critical role in the successful implementation of the Digital Twin (DT) seen as a holistic approach: starting from the early conception and design phases, where models of a wide variety of types are supporting the process, afterwards stepping into the production, including validation and verification phases, right up to the final phases where the product is to be delivered and the end user needs to be trained to effectively make use of it, and to sustain it during the entire life cycle.

Navantia is facing the incorporation of the Digital Twin into the internal processes and delivered products as a differential factor, adding significant value not only to the production processes but also to the system's life cycle. During the operation of the systems, Modelling and Simulation are becoming more and more important for end user training, especially in complex scenarios, and to enhance the system maintenance, where models are also used to carry out maintenance intervention before the system fails, preventing unplanned downtime.

This paper will show Navantia's view on the Digital Twin in the Smart Factory, and the use of M&S techniques to develop tools for User Training and System Maintenance.

1.0 INTRODUCTION

One of the most attractive investments in relation to enterprise digital transformation is the implementation of the digital twin concept in its products development roadmap, achieving a truly smart product portfolio. New value-added services exploiting this digital twin are open in new formats, either human centred and/or machine centred. Customer and contractor are benefited from that in their respective interest spheres, specifically the use experience including the availability and performance for navies, and the product development improvements for the shipbuilder.

These two spheres of interest overlap in terms of opportunities (e.g. efficiency improvement, asset's running cost reduction, etc) but diverge with respect to specific use case's goals. Naval shipbuilder's improvements

are mainly achieved in the design and development phases. Customers will reap improvements in operation and sustainment phases. Due to intrinsic uncertainties in terms of DT requirements fulfilment including an optimistic target ambition level, the DT development must be evolutive in such a way that investment and return criteria is addressed as an iterative process. The agile methodology provides the basic concept for achieving it. Digital twin implementation evolutive strategy is a must and scalability and robustness are key characteristics for harmonizing investment level and profit return in each step.

Naval shipbuilding deals with complex systems, so digital twin implementation level must be progressive and evolutive as well, in terms of enabling technology maturity and complex modelling algorithms availability. Overall investment is significant so incremental waves in digital twin's functionality specification is unavoidable, ranging between functional models of simple systems up to adding health prediction along time, extension to other systems with increased complexity up to extending this concept to the integrated System of Systems as it is a modern naval ship.

Navantia's digital transformation plan includes new smart product and services development programs. This paper deals with challenges derived from DT strategy and rationale for digital twin investment, objectives and technology bases, the Digital Twin Methodology approach and the step-by-step agile development, the conceptual architecture and system definition, and finally some references about real cases and future developments.

2.0 NAVANTIA'S DIGITAL TWIN APPROACH

2.1 Rationale for Digital Twin Investment

There are plenty of reasons why shipbuilders and naval assets owners must adhere to Digital Twin development and implementation. The benefits are at least those already achieved by other industry sectors stakeholders, in general benefits from having product configuration and real status fully characterized, but especially since naval assets operate at open seas with limited reinforcing deployment capability for repairing or operating by skilled people. It is also remarkable the life cycle cost reduction (15-20% is a widely accepted improvement for smart maintenance functionalities) along with the safer operation and higher availability of the assets for the mission. A highly efficient Navy is the overall target of many nations with limited defence budget.

DT as a high-resolution digital replica allows crew and land personnel, both navy and shipbuilder, to know the status of different parts of the ship and personnel integrated as a system.

Availability for the operations and consequently readiness for the mission's understanding is much faster as DT functions using a central information system both for equipment and people status. Systems and components behaviour monitoring with respect to historic data and against to their corresponding models, allow for detecting anomalies early, giving time to the system to anticipate the symptom, giving time before incurring in malfunctions or eventually a failure.

Basic components of a DT are the Digital Mock up (DMU) with the static or persistent product description and behaviour characterization information structured in a data base along with configuration management tools, and the dynamic information compiler where product as an asset shows the real status.

DT is consequently an information system with advance data and model's management capabilities, with application's development and execution environment for exploiting this digital information as a set of smart assistants to the relevant end-user.

As it is described in this paper, DT is an overarching technology that involves and puts in play more than 12

digital transformation technologies with the goal of providing better products to customer (safer and easier to operate, higher maintainability, achieving more performance, etc).

2.2 Objectives and Technology Bases

The main objective of the Digital Twin is to enable the replicability of real things like those on board a naval asset, as reliable and confident cyber-physical systems. There are different complexity levels to be faced and integrated up to getting a hierarchy of well-structured lower complexity element's digital twins. A naval ship DT will consist consequently of a set of system's DTs which at the same time will be a set of element's DTs. Smart products consist of smart systems composed of smart elements (things), all with analysis capabilities and interconnected.

Smart attribute for things will consequently include computing and communication capabilities suitable to recognize its own functional and health status and to communicate with other elements in the upper and lower levels of the product hierarchy in terms of orchestration.

Intelligence level steps are initiated from implementing simple algorithms and a basic human to machine interface, up to complex artificial intelligence algorithms capable of extracting deep insights suitable to support upper level's decision or eventually to even take those decisions, this will be possible once situation awareness and evolution estimation achieves required maturity and confidence.

Enclosed figure shows the different goals for smart products development.

As a summary, objectives in the different evolution staircase steps must be aligned with enabling technology maturity and availability. It is mandatory to specify basic technology and specifically derived needs for addressing each step for solving either more complex systems or simplest one's implementation.

Each product must be broken down allocating priority to systems returning high value in the short term to customers and/or developing company.

2.3 DT Methodology Approach

In accordance with prioritizing objectives in terms of service's potential attractiveness for customer, considering reliability, total cost of ownership, functional and performance capabilities as well as shipbuilder interest in terms of product development's efficiency improvement for achieving the digital return of investment, the corresponding target specifications and goals must be sequenced in time.

A high demanding target requirement in a short-term interval would require a high investment and a high-risk profile particularly if the necessary technology is still not sufficiently mature and vice versa, if the goals were too basic they would not allow to drive with enough intensity to build a robust roadmap.

A robust foundation base from which models and data are being managed for performing the right analytics is paramount for success.

2.4 DT Stepped and Agile Development

Navantia is adopting an agile methodology for establishing technology and modelling robust foundations, addressing only one type of challenge at a time and scaling results for feeding back an incremental number of targets and/or its level of complexity.

DT is currently being managed at concept development stage through a moderate low investment with short

term validation loop in terms of results evaluation, scalability and progression climbing in the ambition level staircase.

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2.5 Conceptual Architecture and System Definition

The architecture of reference for DT must be at least modular, scalable, data oriented and driven. It consists practically of an information system with a runtime execution infrastructure providing basic data servers to support digital mock up data and behaviour models, an application server for applications either supporting analytics functions or other runtime managers in form of a set of applications. Once product virtual part is activated the DT shall get and record historic data, acting as an alive dynamic real status settler. DT must solve the needs of getting and aggregating adequate real-time data, exploiting functional and health behaviour models as this pre-conditionate data processing reducing ambiguous results and improving outcome value.

DT conceptual architecture for Digital Twin at Navantia is showed in the following figure:

Product DT Conceptual Architecture

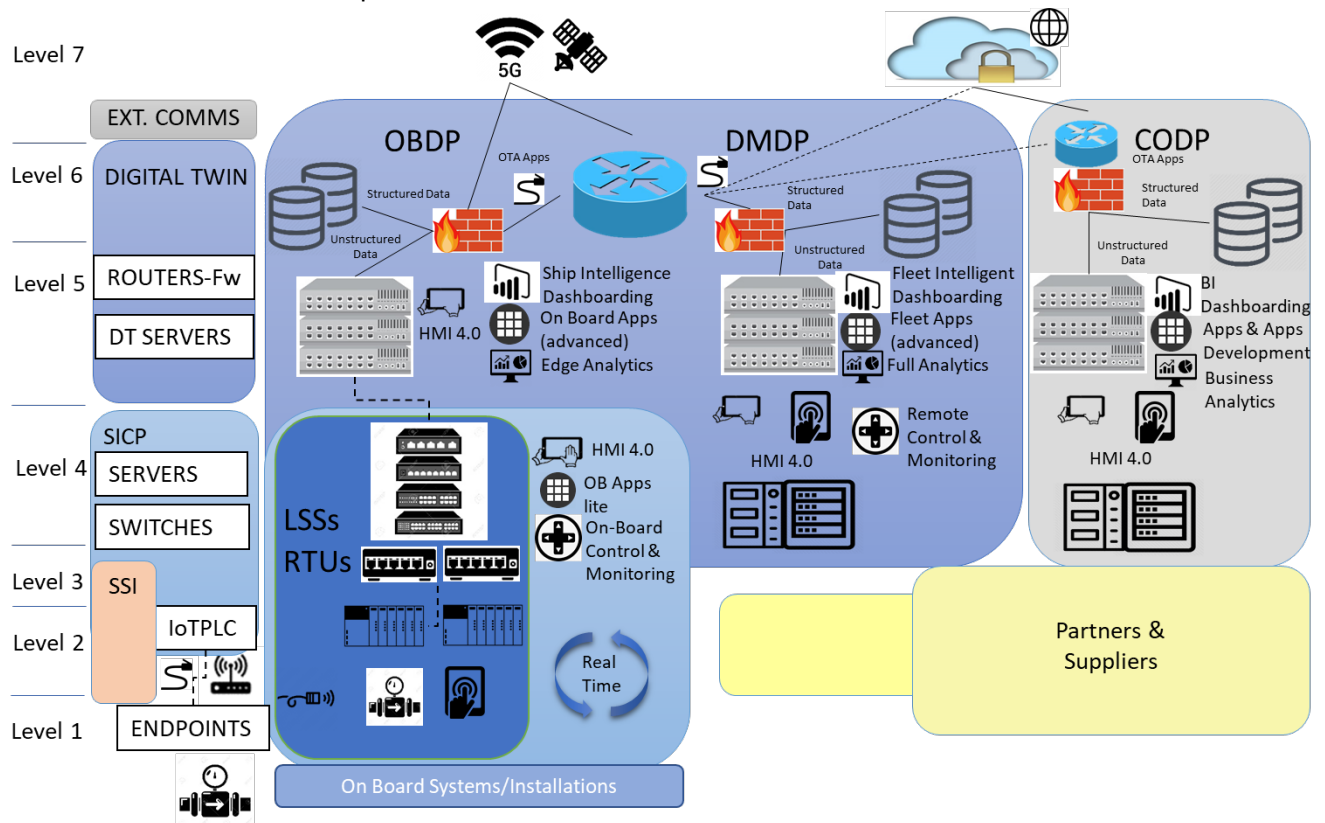


Figure 1. Product DT Conceptual Architecture

In this figure there are 6 levels of data management and decisions, the level 1 where there are simplest things as equipment or components, allow for a basic smart capability (processing simple algorithms with a reduced time response), the level 2 where the smart system uses IoT ready PLCs to allow policy directives for execution and orchestration of level 1 smart equipment, level 3 represents edge computing resource level, including integrated services system (SSI). Level 4 contains an enhanced IPMS (SICP in the figure) for health management as well as whole platform systems functionality management. Level 5 comprises of on-board digital twin digital platform enabling for use case interest analytics execution as well as managing the digital mock-up data set and applied algorithms under applications developed within a configuration management framework. Level 6 implements other digital platforms part of the DT eco-system normally at land (end user, Navantia). Level 7 represents the cloud resources, when needed, being under control in terms of cybersecurity.

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Architecture must deal consequently with functions managing static data, simple models (digital mock-up or DMU) and basic engineering behavioural models as well as dynamic data and advanced models using machine learning or deep algorithms.

Integrated Platform Monitoring System (IPMS) will continue evolving, managing ship platform subsystems, taking smart actions over real time decisions influencing the ship's systems whilst DT goal is to establish the general operations scenario framework parameters for IPMS and decision makers (on board crew, off board crew and/or AI algorithms).

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DT architecture must incorporate enough on-board processing capabilities for closing the loop for action at corresponding information management levels for these dark situations. Cloud computing must switch to act as a private distributed cloud, an on-board cloud, or as normally overall designated edge computing when sailing in blue seas.

When ships approach the coast, these loops can be wider as interconnection with land infrastructures is available. Maximum capability is considered when ship is in the naval base peer with maximum communication capabilities within system platforms communication range and the cloud.

Due to the sensitivity of the information supported in a DT, all elements of the architecture must be secured in terms of cybersecurity.

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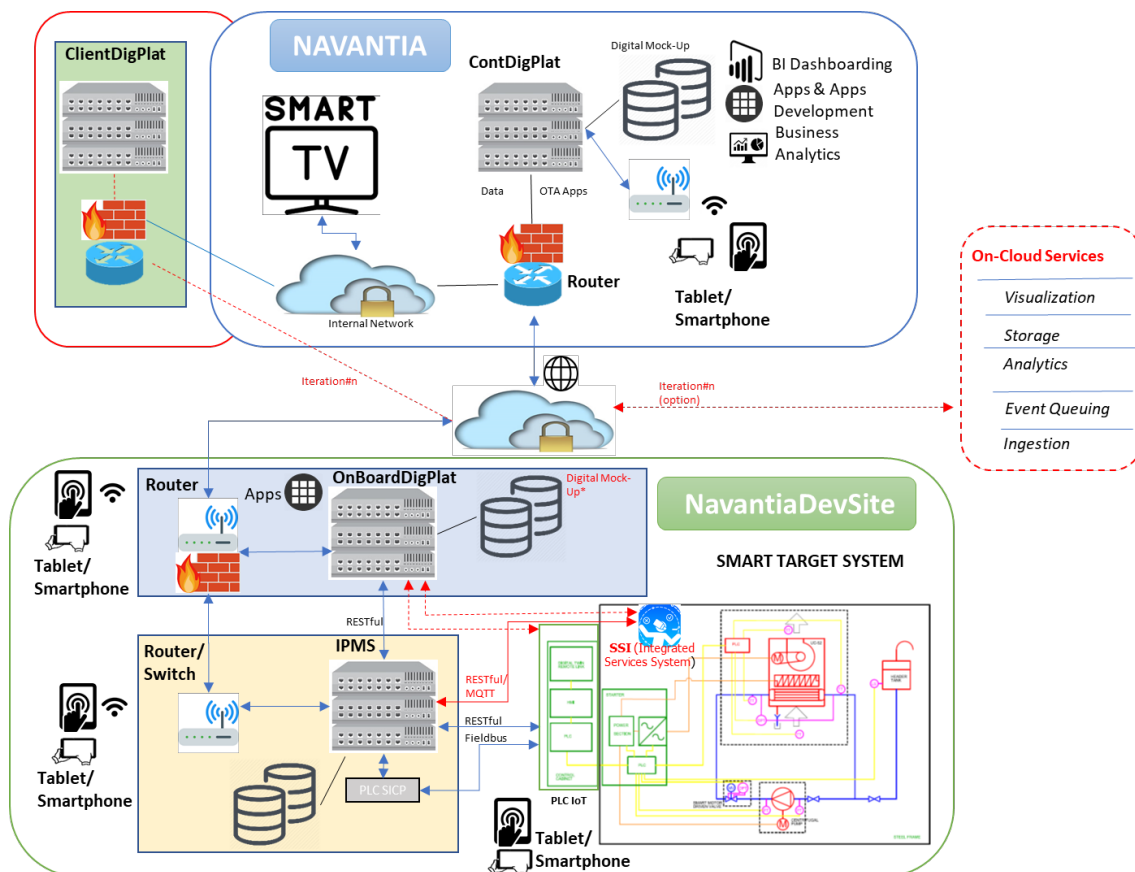


Figure 2. Initial DT Minimum Viable Product Experience

New ships are currently under development being this experience of great value in showing the right ways when it comes to dimensioning a DT. Flexibility to upgrade and scale for custom-specific requirements is embedded in the approach.

Finally, autonomous and/or autonomous for X ships are in the further levels of the roadmap. Here, solutions robustness must be maximum and dynamic situational awareness based on self-learning algorithms are key for success.

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New F110 class frigate includes a Digital Twin exploiting several customer interest dimensions, the operations and life cycle management for total ownership cost reduction during the expected life cycle span, improving reaction time in case of incidents either derived from a damage or a fault/casualty, etc.

This DT system uses all architecture levels as consisting of land-based installation digital platform at customer premises as well as shipbuilder, and the corresponding on-board installation in each of the frigates. Those data aggregation and processing capabilities requiring intensive data analysis could be developed off-board but synchronized with the overall DT platform ecosystem, using a dedicated analysis centre capable to interchange improved and calibrated algorithms in the usage applications from land to sea assets. Configuration management is a cornerstone for controlling each ship as built configuration and as sustained one either for hardware, for digital mock up and for applications suite update over the air (OTA).

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In terms of future developments, DT applications will be extended in accordance with Customer and Navantia needs once a broad data model and exploitation policy is consolidated. New digital services are being defined to be supported using smart apps and assistants.

The Appendix 1 provides further details of one of the capabilities to be incorporated into the DT, the NAVANTIS training suite, that is a family of products and tools under development with existing successful results to train the manoeuvring and piloting of the ship in an immersive and realistic environment, that is also integrating additional already developed functionalities for Combat System and maintenance training, and finally will provide an integrated environment to facilitate the training at different levels.

Appendix 1

Navantia Training Integrated System (NAVANTIS)

As said previously, Navantia is facing the DT development and implementation through an agile approach, to de-risk the investment and elude inappropriate decisions, and to take advantage of existing developments already undertaken to reach intermediate goals that cover a portion of the overarching solution. NAVANTIS is one example of this, since it is an already developed system to provide an integrated training solution to a variety of necessities, from the early phases to educate the user in the maintenance of the system, to the final phases to provide an interactive and realistic simulation to train the end user in the operation of the system at any level.

A.1.0. WHAT IS NAVANTIS

NAVANTIS is a new family of products and tools oriented to support the end user training in the operation and maintenance of the Navantia ships and their systems. It has a modular and scalable architecture to be able to adapt to any required configuration of ships and systems, and also be ready to accommodate any future equipment and capabilities during the life cycle of the delivered products. The next figure shows the general structure of Navantis concept:

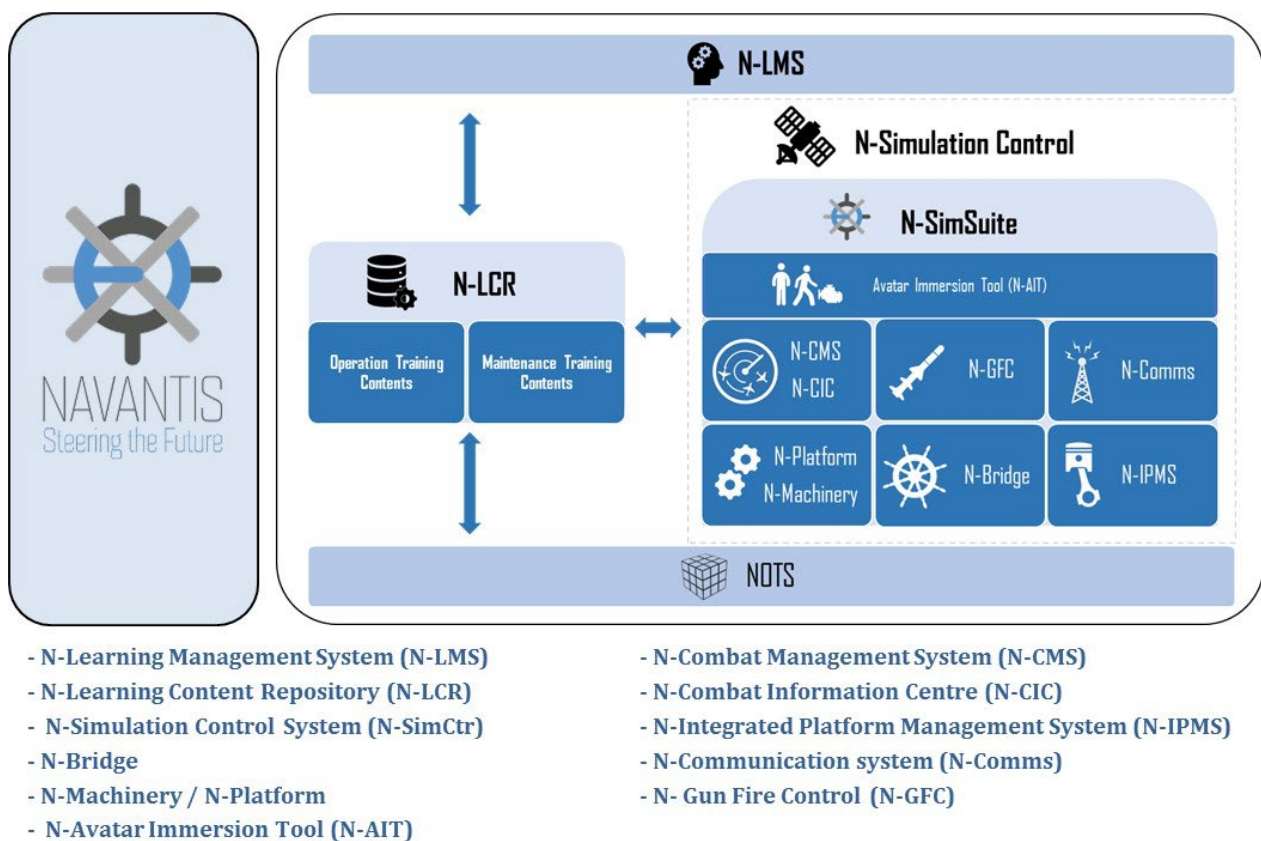


Figure A- 1. NAVANTIS Conceptual Architecture

NAVANTIS is the integrated training solution for ships designed by Navantia. The training is carried out in two stages:

- An initial stage based on e-learning, for a first contact with the ship systems. This first stage allows access to mass training of as many members of the crew as necessary. Since it is based on Web technology, it does not involve resources or take up specific premises, allowing the crews to become familiar with the tools needed to operate a vessel.
- A second in-depth stage is carried out using hands-on exercises, where the trainees operate, by means of highly realistic virtualized HMI interfaces, on real-time simulators. This second stage is for selected crew members with specific responsibilities and the training sessions take place in dedicated NAVANTIS classrooms.



Figure A- 2. NAVANTIS Typical Layout

A.1.1. Navantis Classroom

The NAVANTIS classroom houses the equipment used to operate on the simulated vessels. Its main features are:

- It is modular and **configurable**; generic NAVANTIS hardware modules are arranged in the room to suit biggest platform and then specific software for each particular ship is loaded for every training session. A single classroom covers all single-ship simulator training.
- Software specific modules provide **particular ship HMI**. Virtualized hardware panels are implemented at a high degree of detail resulting in a close familiarization with real hardware interfaces of each ship in particular.
- It **integrates** local platform systems operation training, remote platform operation training (IPMS), bridge crew training, Communications and more.
- It is **inter-connectable** with other NAVANTIS classrooms.
- It allows to impart **collaborative** training, so that the key members of the ship's crews interact together in the same session and face the same scenarios in a coordinated manner.

- The NAVANTIS facilities are **multiuse** since not only can they be of use as a training classroom, but also as an engineering laboratory to debrief real ship logs in order to study any real platform issue, discuss or develop new IPMS features and also test new IPMS versions before being installed on board.

The disciplines which are contemplated as potential contributors to NAVANTIS are:

- The ship Platform equipment and systems (engines, valves, rudders, pumps,...)
- Integrated Platform Management System
- Navigation System
- Communications System
- Combat System

All systems end up having their representation or their effects in the virtual natural environment. During the training sessions the environment outside the vessel is represented, aiming to provide the operator with a subjective view of the physical surroundings. Each NAVANTIS room allows each of the different crew members to see from their own perspective both the world that is outside and the environment within the ship.

A.1.2. Navantis Training Levels

NAVANTIS is structured with different training levels within a single product, as explained below.

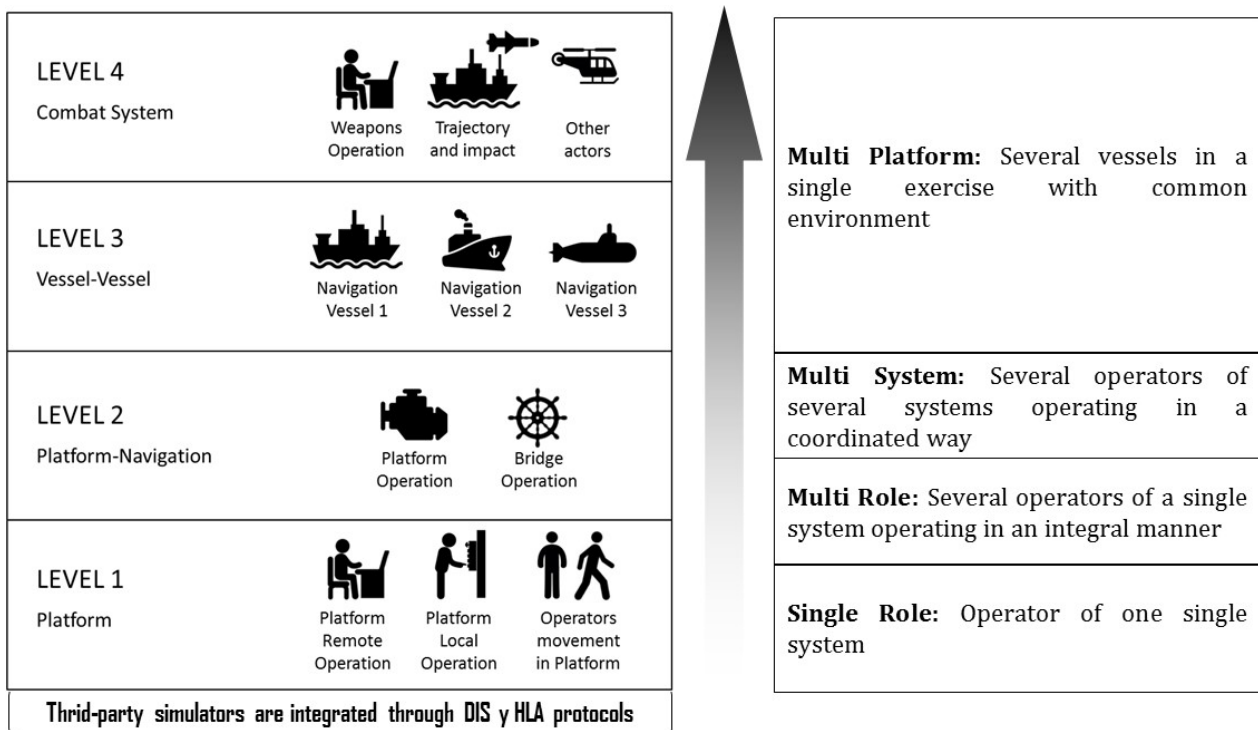


Figure A- 3. NAVANTIS Training Levels

- LEVEL 1: Platform.

NAVANTIS teaches the crew how to operate the multiple ship platform equipment and systems that make up the ship Platform, combining the remote operation from the Integrated Platform Management System (IPMS) consoles, with the local operation at the equipment and system local operation panels. Mechanical, Electrical and Damage Control specialists will be able to execute control actions by acting on the remote interface (IPMS mimics) and from the local control panels (by means of virtualized physical panels). Above all, they will learn to coordinate among themselves and they will also gain a deep ship geographic knowledge of the physical environment where they will have to move.

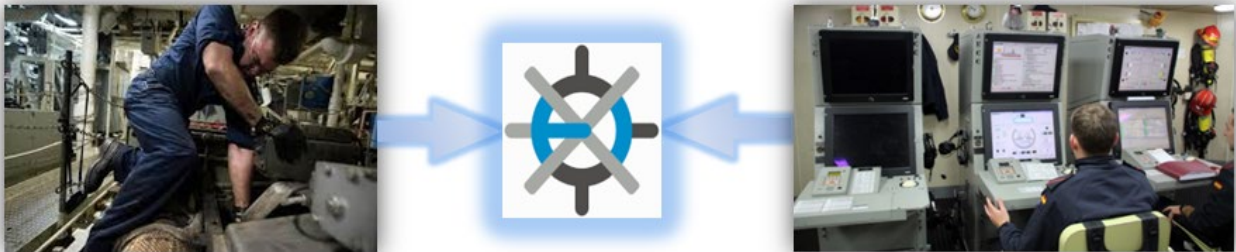


Figure A- 4. Level 1 training: how to operate systems

- LEVEL 2: Platform – Navigation.

NAVANTIS has the capacity to simultaneously cover the Engine operators training and the Bridge operators training within the same ship, covering to the maximum detail all aspects each type of operator must know, but also contemplating the interrelations that there exist between the two worlds. For example, if while the Bridge operator is practicing a manoeuvre of entering and docking at the port, a problem rises in the power generation plant whose consequence is a black out of the ship, the Engine operator must know how to react to resolve the situation in the minimum possible time and recover bow thrusters availability to the Bridge operator. During this transitory risk situation there must exist a dialogue and coordination between both kinds of crews, which is necessary to have practiced in advance. Engine operators operate virtually from locations such as the machinery control room, the electrical switchboards or the engine rooms, and get a good vision of the ship from the inside. At the same time, the Bridge operators act virtually from the bridge and, through their windows and the navigation equipment located at the steering console (nautical charts, radar, AIS), get a vision of what happens outside the vessel.

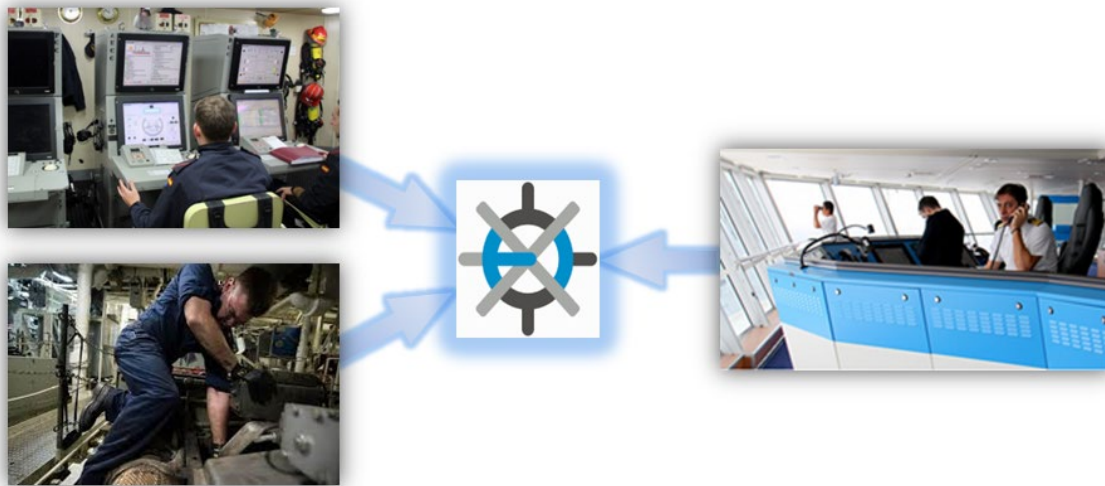


Figure A- 5. Level 2 training: manning the ship

- LEVEL 3: Ship-to-Ship

NAVANTIS takes a step beyond the concept of integrated platform training, since it allows joint and coordinated training operations execution involving different vessels and crews. For example, landing crafts docking manoeuvres to and from amphibious transport vessels, practice any ship's RHIB surveillance missions or even ship to ship supply in Replenishment At Sea (RAS) manoeuvres. NAVANTIS power is particularly demonstrated with this last specific scenario since allows ship to ship bridge pilots coordination, together with crew engineers training on fluids or loads transfer once the connection is achieved.



Figure A- 6. Level 3 training: Ship-to-Ship

- LEVEL 4: Combat System.

Once Navantia vessels training is fulfilled at platform and Navigation level, NAVANTIS can also incorporate other training solutions for systems or crafts existing on board. Full ship mission simulator is then complete. This is achieved since NAVANTIS has been developed using Military Scenario Definition Language (MSDL) and distributed simulator interface standards. Exercise situation is distributed via data-link simulation network to all participants, sharing virtual representation in a coordinated coherent way.



Figure A- 7. Level 4 training: full ship manning

NAVANTIS in its concept, is a live product and not exclusive to a single ship or Navy. Depending on the protocols established international training sessions among NAVANTIS centres could even be held.

An inherent feature of NAVANTIS consists of transferring to the professional training certain concepts typical of the video gaming world, with the goal of turning the apprenticeship into something attractive and user friendly for the trainees, thereby increasing their level of interest and participation. This is achieved by using very realistic visual and sound interfaces, and by introducing challenges to the trainees to promote competitiveness.



Figure A- 8. NAVANTIS classroom



Navantia's Digital Twin Implementation Perspective in Military Naval Platform Life Cycle

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ABSTRACT

Digital transformation is a cornerstone to increase efficiency and productivity in today's businesses and enterprises, and Modelling and Simulation (M&S) play a critical role in the successful implementation of the Digital Twin (DT) seen as a holistic approach: starting from the early conception and design phases, where models of a wide variety of types are supporting the process, afterwards stepping into the production, including validation and verification phases, right up to the final phases where the product is to be delivered and the end user needs to be trained to effectively make use of it, and to sustain it during the entire life cycle.

Navantia is facing the incorporation of the Digital Twin into the internal processes and delivered products as a differential factor, adding significant value not only to the production processes but also to the system's life cycle. During the operation of the systems, Modelling and Simulation are becoming more and more important for end user training, especially in complex scenarios, and to enhance the system maintenance, where models are also used to carry out maintenance intervention before the system fails, preventing unplanned downtime.

This paper will show Navantia's view on the Digital Twin in the Smart Factory, and the use of M&S techniques to develop tools for User Training and System Maintenance.

1.0 INTRODUCTION

One of the most attractive investments in relation to enterprise digital transformation is the implementation of the digital twin concept in its products development roadmap, achieving a truly smart product portfolio. New value-added services exploiting this digital twin are open in new formats, either human centred and/or machine centred. Customer and contractor are benefited from that in their respective interest spheres, specifically the use experience including the availability and performance for navies, and the product development improvements for the shipbuilder.

These two spheres of interest overlap in terms of opportunities (e.g. efficiency improvement, asset's running cost reduction, etc) but diverge with respect to specific use case's goals. Naval shipbuilder's improvements

are mainly achieved in the design and development phases. Customers will reap improvements in operation and sustainment phases. Due to intrinsic uncertainties in terms of DT requirements fulfilment including an optimistic target ambition level, the DT development must be evolutive in such a way that investment and return criteria is addressed as an iterative process. The agile methodology provides the basic concept for achieving it. Digital twin implementation evolutive strategy is a must and scalability and robustness are key characteristics for harmonizing investment level and profit return in each step.

Naval shipbuilding deals with complex systems, so digital twin implementation level must be progressive and evolutive as well, in terms of enabling technology maturity and complex modelling algorithms availability. Overall investment is significant so incremental waves in digital twin's functionality specification is unavoidable, ranging between functional models of simple systems up to adding health prediction along time, extension to other systems with increased complexity up to extending this concept to the integrated System of Systems as it is a modern naval ship.

Navantia's digital transformation plan includes new smart product and services development programs. This paper deals with challenges derived from DT strategy and rationale for digital twin investment, objectives and technology bases, the Digital Twin Methodology approach and the step-by-step agile development, the conceptual architecture and system definition, and finally some references about real cases and future developments.

2.0 NAVANTIA'S DIGITAL TWIN APPROACH

2.1 Rationale for Digital Twin Investment

There are plenty of reasons why shipbuilders and naval assets owners must adhere to Digital Twin development and implementation. The benefits are at least those already achieved by other industry sectors stakeholders, in general benefits from having product configuration and real status fully characterized, but especially since naval assets operate at open seas with limited reinforcing deployment capability for repairing or operating by skilled people. It is also remarkable the life cycle cost reduction (15-20% is a widely accepted improvement for smart maintenance functionalities) along with the safer operation and higher availability of the assets for the mission. A highly efficient Navy is the overall target of many nations with limited defence budget.

DT as a high-resolution digital replica allows crew and land personnel, both navy and shipbuilder, to know the status of different parts of the ship and personnel integrated as a system.

Availability for the operations and consequently readiness for the mission's understanding is much faster as DT functions using a central information system both for equipment and people status. Systems and components behaviour monitoring with respect to historic data and against to their corresponding models, allow for detecting anomalies early, giving time to the system to anticipate the symptom, giving time before incurring in malfunctions or eventually a failure.

Basic components of a DT are the Digital Mock up (DMU) with the static or persistent product description and behaviour characterization information structured in a data base along with configuration management tools, and the dynamic information compiler where product as an asset shows the real status.

DT is consequently an information system with advance data and model's management capabilities, with application's development and execution environment for exploiting this digital information as a set of smart assistants to the relevant end-user.

As it is described in this paper, DT is an overarching technology that involves and puts in play more than 12

digital transformation technologies with the goal of providing better products to customer (safer and easier to operate, higher maintainability, achieving more performance, etc).

2.2 Objectives and Technology Bases

The main objective of the Digital Twin is to enable the replicability of real things like those on board a naval asset, as reliable and confident cyber-physical systems. There are different complexity levels to be faced and integrated up to getting a hierarchy of well-structured lower complexity element's digital twins. A naval ship DT will consist consequently of a set of system's DTs which at the same time will be a set of element's DTs. Smart products consist of smart systems composed of smart elements (things), all with analysis capabilities and interconnected.

Smart attribute for things will consequently include computing and communication capabilities suitable to recognize its own functional and health status and to communicate with other elements in the upper and lower levels of the product hierarchy in terms of orchestration.

Intelligence level steps are initiated from implementing simple algorithms and a basic human to machine interface, up to complex artificial intelligence algorithms capable of extracting deep insights suitable to support upper level's decision or eventually to even take those decisions, this will be possible once situation awareness and evolution estimation achieves required maturity and confidence.

Enclosed figure shows the different goals for smart products development.

As a summary, objectives in the different evolution staircase steps must be aligned with enabling technology maturity and availability. It is mandatory to specify basic technology and specifically derived needs for addressing each step for solving either more complex systems or simplest one's implementation.

Each product must be broken down allocating priority to systems returning high value in the short term to customers and/or developing company.

2.3 DT Methodology Approach

In accordance with prioritizing objectives in terms of service's potential attractiveness for customer, considering reliability, total cost of ownership, functional and performance capabilities as well as shipbuilder interest in terms of product development's efficiency improvement for achieving the digital return of investment, the corresponding target specifications and goals must be sequenced in time.

A high demanding target requirement in a short-term interval would require a high investment and a high-risk profile particularly if the necessary technology is still not sufficiently mature and vice versa, if the goals were too basic they would not allow to drive with enough intensity to build a robust roadmap.

A robust foundation base from which models and data are being managed for performing the right analytics is paramount for success.

2.4 DT Stepped and Agile Development

Navantia is adopting an agile methodology for establishing technology and modelling robust foundations, addressing only one type of challenge at a time and scaling results for feeding back an incremental number of targets and/or its level of complexity.

DT is currently being managed at concept development stage through a moderate low investment with short

term validation loop in terms of results evaluation, scalability and progression climbing in the ambition level staircase.

Company executive level approves each investment, once the program is running, providing an instrument for tracking real interest in internal axis (efficiency, smart integration, quality, etc) and external axis (customer demands, real value provided and overall satisfaction). New advanced services supported by DTs are potentially huge, so it constitutes the practical target. Applications and configuration management for either hardware and software require a new system architecture for DTs.

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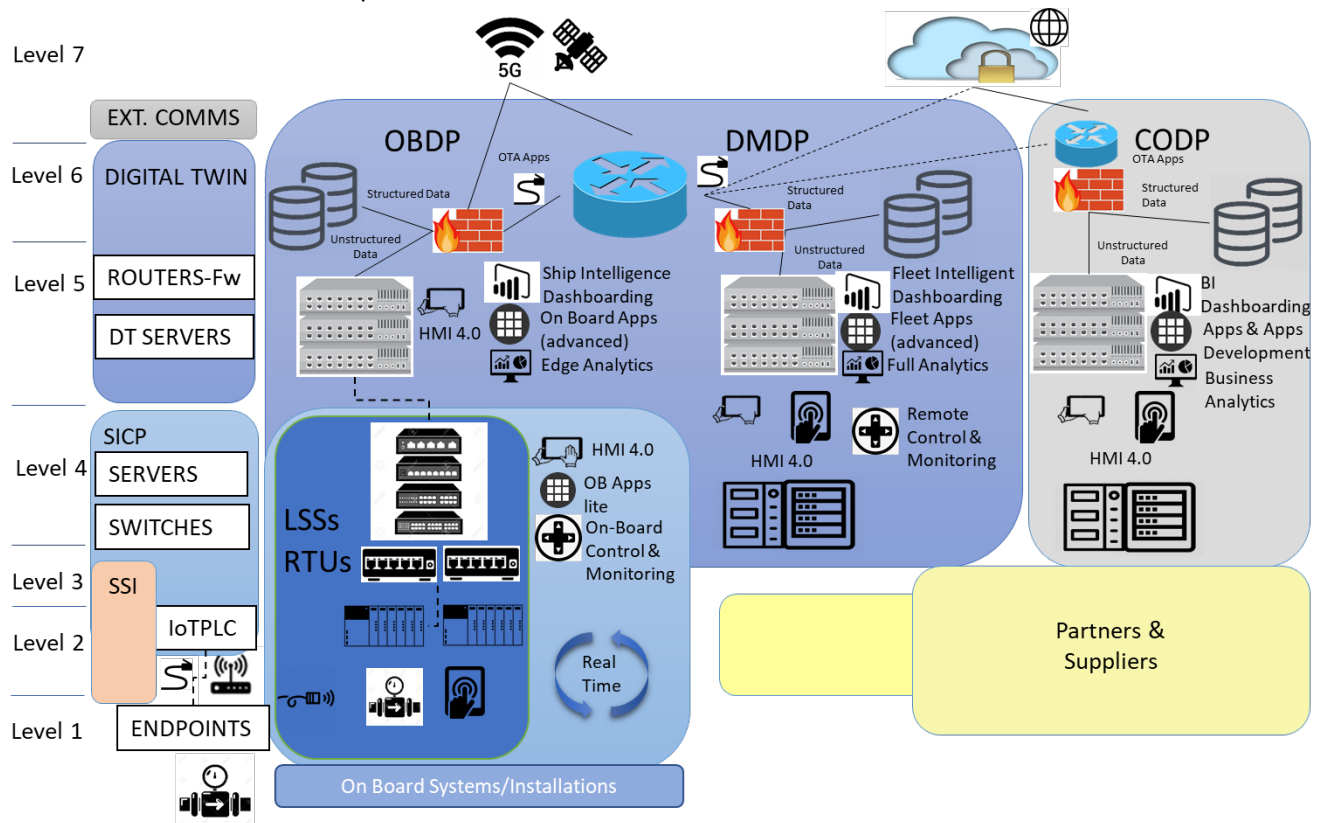


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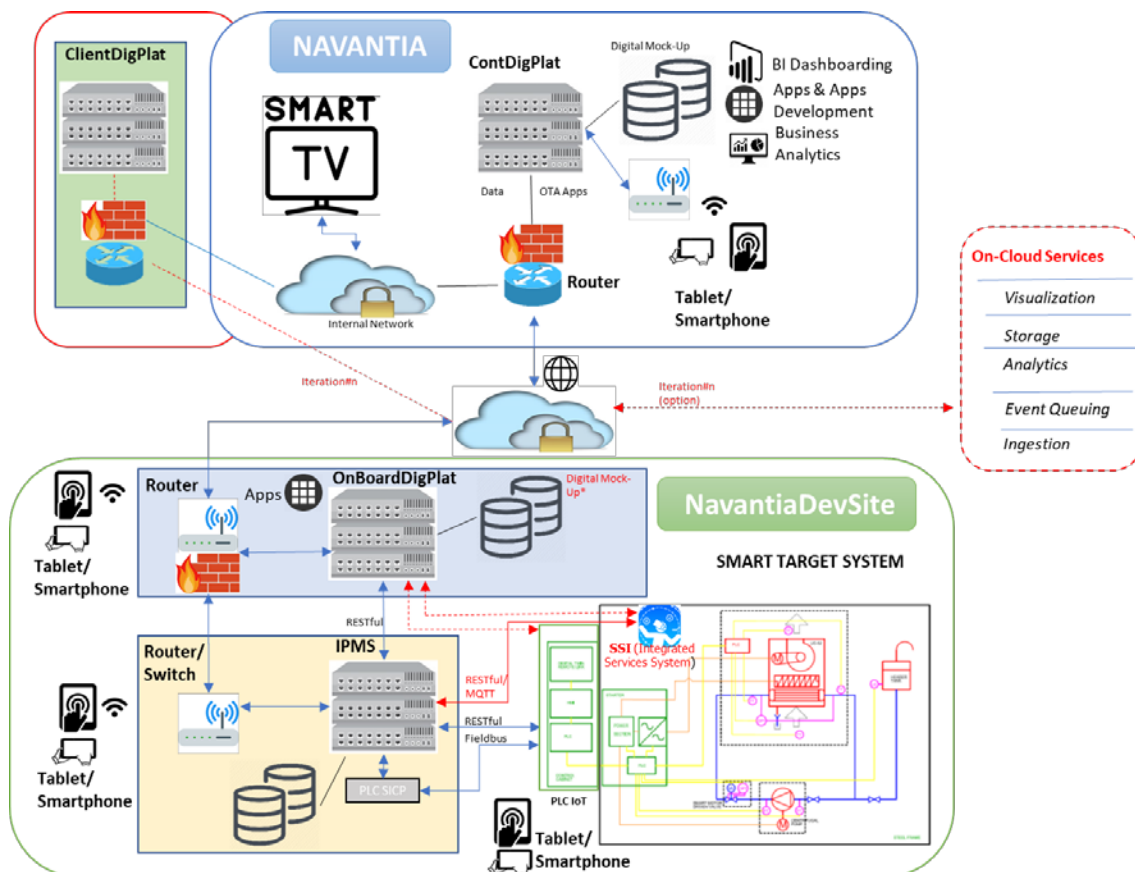


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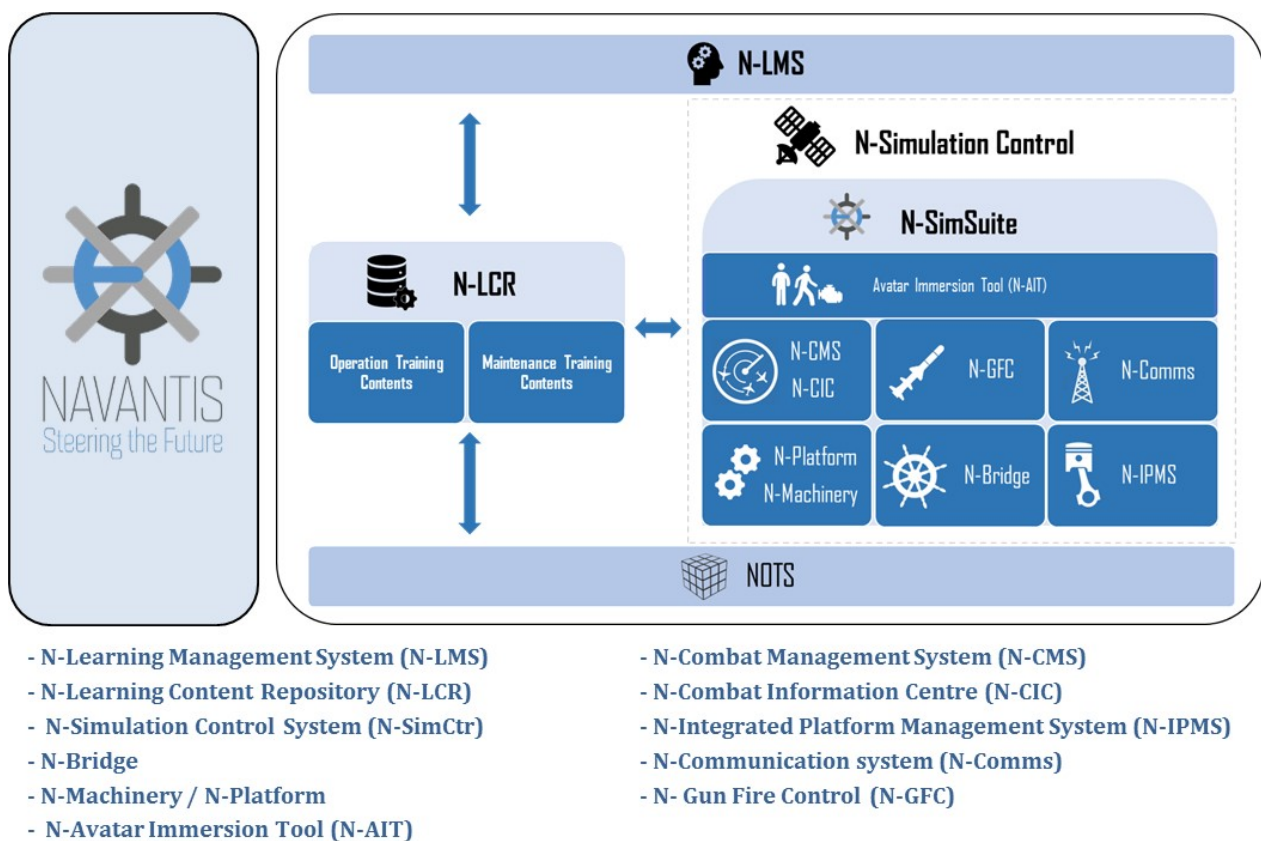


Figure A- 1. NAVANTIS Conceptual Architecture

NAVANTIS is the integrated training solution for ships designed by Navantia. The training is carried out in two stages:

- An initial stage based on e-learning, for a first contact with the ship systems. This first stage allows access to mass training of as many members of the crew as necessary. Since it is based on Web technology, it does not involve resources or take up specific premises, allowing the crews to become familiar with the tools needed to operate a vessel.
- A second in-depth stage is carried out using hands-on exercises, where the trainees operate, by means of highly realistic virtualized HMI interfaces, on real-time simulators. This second stage is for selected crew members with specific responsibilities and the training sessions take place in dedicated NAVANTIS classrooms.



Figure A- 2. NAVANTIS Typical Layout

A.1.1. Navantis Classroom

The NAVANTIS classroom houses the equipment used to operate on the simulated vessels. Its main features are:

- It is modular and **configurable**; generic NAVANTIS hardware modules are arranged in the room to suit biggest platform and then specific software for each particular ship is loaded for every training session. A single classroom covers all single-ship simulator training.
- Software specific modules provide **particular ship HMI**. Virtualized hardware panels are implemented at a high degree of detail resulting in a close familiarization with real hardware interfaces of each ship in particular.
- It **integrates** local platform systems operation training, remote platform operation training (IPMS), bridge crew training, Communications and more.
- It is **inter-connectable** with other NAVANTIS classrooms.
- It allows to impart **collaborative** training, so that the key members of the ship's crews interact together in the same session and face the same scenarios in a coordinated manner.

- The NAVANTIS facilities are **multiuse** since not only can they be of use as a training classroom, but also as an engineering laboratory to debrief real ship logs in order to study any real platform issue, discuss or develop new IPMS features and also test new IPMS versions before being installed on board.

The disciplines which are contemplated as potential contributors to NAVANTIS are:

- The ship Platform equipment and systems (engines, valves, rudders, pumps,...)
- Integrated Platform Management System
- Navigation System
- Communications System
- Combat System

All systems end up having their representation or their effects in the virtual natural environment. During the training sessions the environment outside the vessel is represented, aiming to provide the operator with a subjective view of the physical surroundings. Each NAVANTIS room allows each of the different crew members to see from their own perspective both the world that is outside and the environment within the ship.

A.1.2. Navantis Training Levels

NAVANTIS is structured with different training levels within a single product, as explained below.

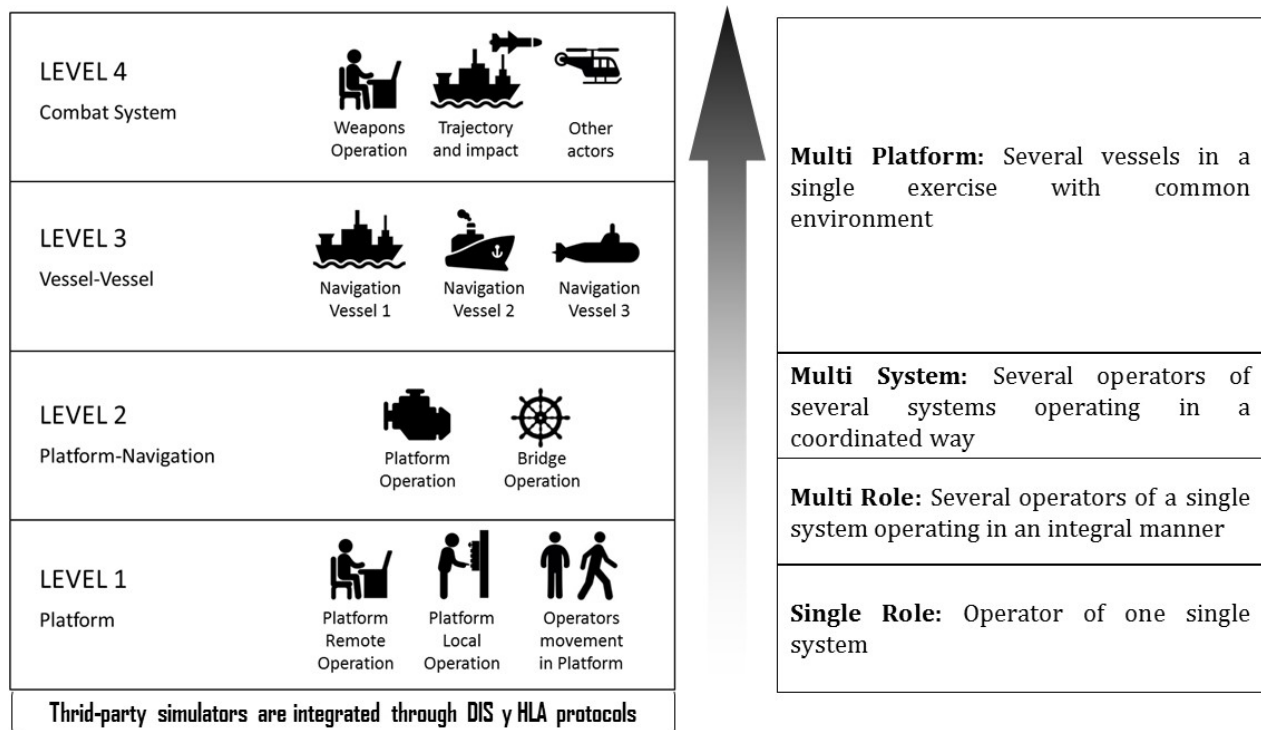


Figure A- 3. NAVANTIS Training Levels

- LEVEL 1: Platform.

NAVANTIS teaches the crew how to operate the multiple ship platform equipment and systems that make up the ship Platform, combining the remote operation from the Integrated Platform Management System (IPMS) consoles, with the local operation at the equipment and system local operation panels. Mechanical, Electrical and Damage Control specialists will be able to execute control actions by acting on the remote interface (IPMS mimics) and from the local control panels (by means of virtualized physical panels). Above all, they will learn to coordinate among themselves and they will also gain a deep ship geographic knowledge of the physical environment where they will have to move.

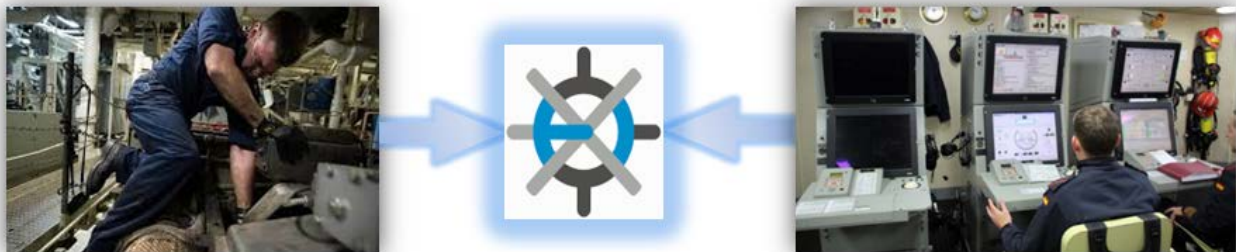


Figure A- 4. Level 1 training: how to operate systems

- LEVEL 2: Platform – Navigation.

NAVANTIS has the capacity to simultaneously cover the Engine operators training and the Bridge operators training within the same ship, covering to the maximum detail all aspects each type of operator must know, but also contemplating the interrelations that there exist between the two worlds. For example, if while the Bridge operator is practicing a manoeuvre of entering and docking at the port, a problem rises in the power generation plant whose consequence is a black out of the ship, the Engine operator must know how to react to resolve the situation in the minimum possible time and recover bow thrusters availability to the Bridge operator. During this transitory risk situation there must exist a dialogue and coordination between both kinds of crews, which is necessary to have practiced in advance. Engine operators operate virtually from locations such as the machinery control room, the electrical switchboards or the engine rooms, and get a good vision of the ship from the inside. At the same time, the Bridge operators act virtually from the bridge and, through their windows and the navigation equipment located at the steering console (nautical charts, radar, AIS), get a vision of what happens outside the vessel.

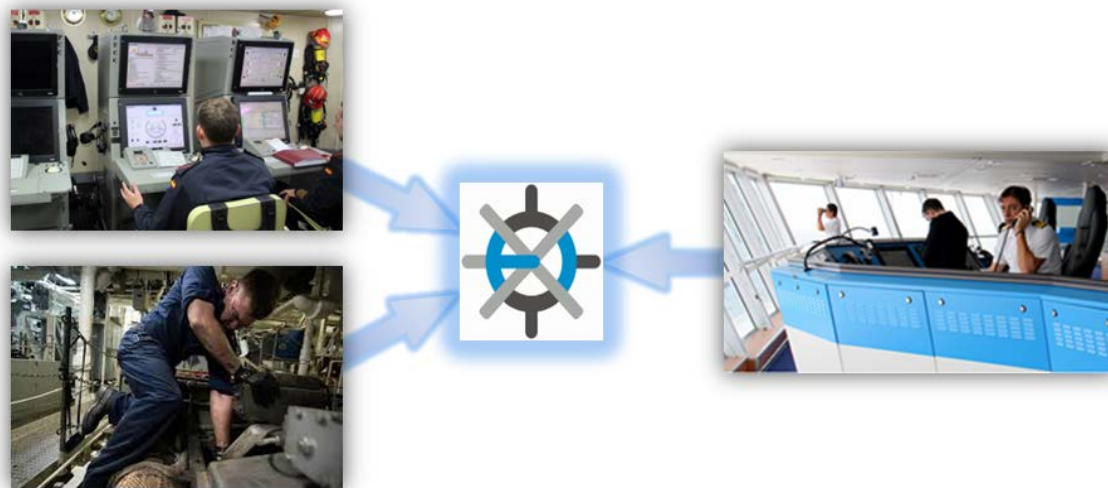


Figure A- 5. Level 2 training: manning the ship

- LEVEL 3: Ship-to-Ship

NAVANTIS takes a step beyond the concept of integrated platform training, since it allows joint and coordinated training operations execution involving different vessels and crews. For example, landing crafts docking manoeuvres to and from amphibious transport vessels, practice any ship's RHIB surveillance missions or even ship to ship supply in Replenishment At Sea (RAS) manoeuvres. NAVANTIS power is particularly demonstrated with this last specific scenario since allows ship to ship bridge pilots coordination, together with crew engineers training on fluids or loads transfer once the connection is achieved.



Figure A- 6. Level 3 training: Ship-to-Ship

- LEVEL 4: Combat System.

Once Navantia vessels training is fulfilled at platform and Navigation level, NAVANTIS can also incorporate other training solutions for systems or crafts existing on board. Full ship mission simulator is then complete. This is achieved since NAVANTIS has been developed using Military Scenario Definition Language (MSDL) and distributed simulator interface standards. Exercise situation is distributed via data-link simulation network to all participants, sharing virtual representation in a coordinated coherent way.



Figure A- 7. Level 4 training: full ship manning

NAVANTIS in its concept, is a live product and not exclusive to a single ship or Navy. Depending on the protocols established international training sessions among NAVANTIS centres could even be held.

An inherent feature of NAVANTIS consists of transferring to the professional training certain concepts typical of the video gaming world, with the goal of turning the apprenticeship into something attractive and user friendly for the trainees, thereby increasing their level of interest and participation. This is achieved by using very realistic visual and sound interfaces, and by introducing challenges to the trainees to promote competitiveness.

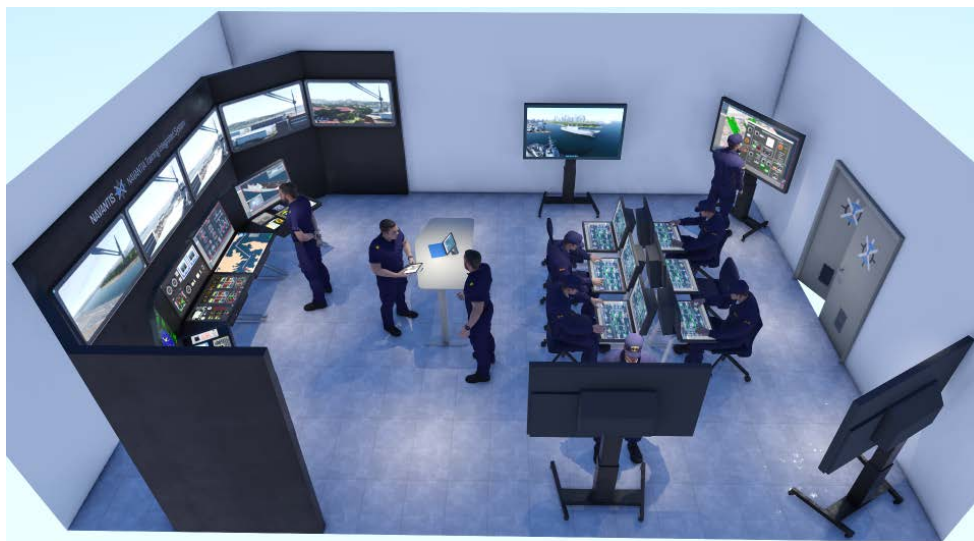


Figure A- 8. NAVANTIS classroom



Preparing for Operational Use of C2-Simulation Interoperation

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ABSTRACT

Technical Activities in the NATO MSG are completing sustained development of a standards-based capability, known as C2SIM, for coalitions to interoperate their national command and control (C2) and simulation systems collectively as part of NATO's Federated Mission Network (FMN). This form of synthetic battlespace can have a great impact on the effectiveness of coalition military operations. The second generation of C2SIM standards from SISO is ready for balloting and afterwards will form the basis of a STANAG. MSG-145 is conducting extensive testing to validate these standards. Several closely related capabilities developed in testing also can ease the path to operational use.

This paper describes those capabilities: (1) C2SIM within Modelling and Simulation as a Service (MSaaS); (2) adoption by the MSCOE of the C2SIM Sandbox distributed development platform; (3) using C2SIM to support operational training in a cyber-active environment; and (4) extension of C2SIM into different domains, exemplified by an Autonomous Systems Extension. C2SIM provides a powerful new, standards-based capability for coalition simulations to support collective training (including cyber effects), planning (including mission analysis) and increasingly important in command and control of Autonomous Systems for military operations. This paper provides important information to prepare for its operational military use.

1.0 INTRODUCTION: C2SIM OVERVIEW

The ability to interoperate command and control (C2 or Mission Command) systems with simulation systems has been an important goal for more than a decade [1]. Over those years the NATO Modelling and Simulation Group (NMSG) has been cooperating with the Simulation Interoperability Standards Organization (SISO) to develop, prototype, and test standards that support that capability. Their shared vision is that members of a coalition will be able to combine their C2 systems and simulation systems collectively into a system-of-systems where simulations are tasked by the C2 systems and in turn provide reports that are displayed on the C2 system just as they would appear due to real-world operations. The resulting system of systems can support training,

course of action analysis, and mission rehearsal for the coalition. Each force element uses the C2 system with which it has trained and is represented by a simulation that represents well its doctrine, resources, and tactics/techniques/procedures. Sharing information this way will result in more effective coalition operations that can happen sooner [2, 3].

Standards enabling the vision described above are well along in development by SISO and expected to reach the balloting phase by the end of 2019. In order to finalize effective standards, the NATO Technical Activity MSG-145 *Operationalization of Command and Control – Simulation Interoperation* (C2SIM) undertook a validation process. This paper describes that process, beginning with the roles and motivations of NATO and SISO, then providing background on C2SIM. After that we will look at the activities of the eight national teams involved most recently and then explain how they enabled validation of C2SIM through a coordinated effort that provided compliant interfaces on six different simulations and one C2 system as well as supporting software. The validation effort took these C2SIM-enabled systems to the NATO Coalition Warrior Interoperability Exercise (CWIX) for detailed testing and then culminated with experimentation, structured as a miniature exercise in distributed mission planning. The paper concludes with lessons learned from the validation process and a view toward the future of C2SIM-based coalition interoperability.

Figure 1 shows the general architecture of a C2SIM coalition. The C2 systems interoperate using a C2 standard; the simulation systems interoperate using a simulation standard; and the system of systems interoperates using C2SIM. A web service is used to replicate C2SIM messages for distribution among the constituent systems and to produce a log that documents results of the operation.

The draft C2SIM standard consists of a text document defining rules and procedures for interoperation and for maintenance of the ontologies; a Core ontology consisting of data classes expected to be needed by any operational simulation; a Standard Military Extension (SMX) with classes applicable to all domains of military activity; and a Land Operations Extension (LOX) to encompass the capability originally provided by MSDL and C-BML and also to serve as an exemplar for future extensions. SMX is logically part of the main C2SIM standard, while LOX forms a new layer on top of Core+SMX.

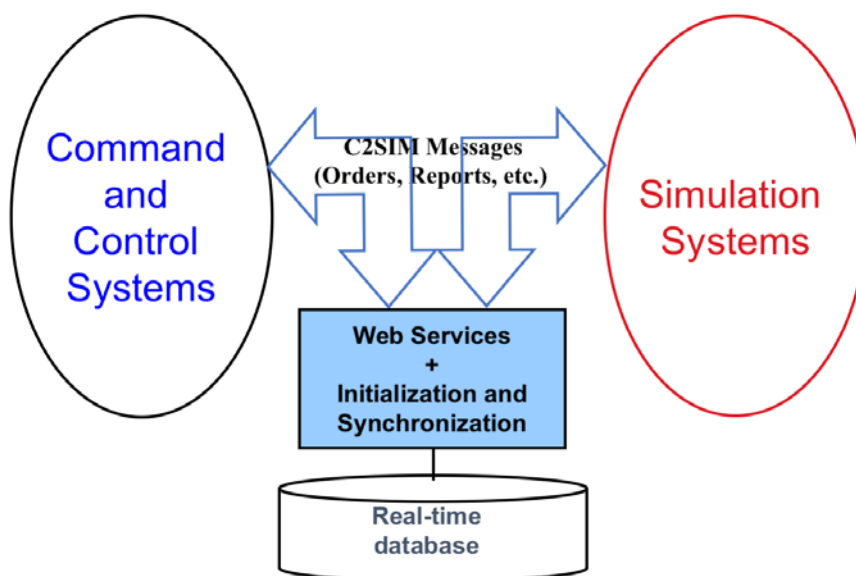


Figure 1: C2SIM Coalition General Architecture

2.0 NATO AND SISO ROLES DEVELOPING C2SIM

The partnership between MSG-145 and the SISO C2SIM Product Development Group (PDG) has been critical in reaching a point where C2SIM can be validated, and even more critical in the validation process. As a collaborative organization of industry, academic and government people, SISO does not have the ability to develop working prototype systems-of-systems or to validate them with international military participation. Conversely, NATO is not in a position to develop industry-based standards. Cooperative work between the two has been needed to create the C2SIM standard.

MSG-145 is the third in a sequence of NATO Technical Activities that has supported development of C2SIM. The first, MSG-048 *Coalition Battle Management Language*, completed validation of the technical feasibility of coalition C2-simulation interoperation. The second, MS-085 *Standardization for C2-Simulation Interoperation* supported and tested the first generation of C2-simulation interoperation standards: the *Military Scenario Definition Language (MSDL)* [4] and the *Coalition Battle Management Language (C-BML)* [5]. A key outcome of MSG-085 was the determination that while MSDL and C-BML can be made to work together, a second-generation standard was needed to achieve effective harmonization; also that the second generation should be designed for extensibility [6]. SISO responded by forming a merged PDG with a charter to achieve these things under the unified name C2SIM [7]. A goal of MSG-145 is to base a NATO Standardization Agreement (STANAG) on the C2SIM industry standard.

SISO's activities to create C2SIM have been based on a complete bottom-up review of both C-BML and MSDL with a view to the result serving as the basis for a family of extensions. The C2SIM PDG concluded that the best way to approach this was developing a consistent family of ontologies. Development has been underway since 2014 and recently produced a set of draft ontologies that is ready for implementation, along with an approach to extracting a standard XML schema from the ontologies to support implementation for validation.

3.0 C2SIM AS A SERVICE UNDER MSAAS

Modelling and Simulation as a Service (MSaaS) is a new approach being explored by the STO NMSG Panel for a permanently available, flexible, service-based framework to provide more cost effective availability of Modelling and Simulation (M&S) products, data and processes to a large number of users on-demand.

The NATO MSG-136 *Modelling and Simulation as a Service Implementation* defined MSaaS as “the combination of service-based approaches with ideas taken from cloud computing” [9].

MSG-145 defined the C2SIM Integration Platform (IP) Reference Architecture (RA) using both the NATO C3 Taxonomy [10] and the MSaaS Reference Architecture from NATO MSG-136 [9] as a source for Architecture Building Blocks (ABBs) and Architecture Patterns. The basic idea is to provide C2SIM as a service, defining ABBs linked to the NATO C3 Taxonomy and the M&S extensions defined by NATO MSG-136. Examples of defined ABBs are Message-Oriented Middleware Service (functionality to support the exchange of messages between data producers and consumers, independent of the message format and content) or Mediation Services (middle layer between incompatible producers and consumers of information), built in the system-of-systems experimented by MSG 145.

An experimental platform to provide “C2SIM as a service” is that developed by NATO Modelling and Simulation Centre of Excellence (MSCOE) in collaboration with the Leonardo company. This is a MSaaS cloud-based testbed prototype, named Open Cloud Environment ApplicationN (OCEAN). It offers an embryonic framework made of a combination of hardware, software and services to automate the deployment of M&S tools and applications in a cloud environment. The OCEAN platform offers a unique point of access through a web portal with secure access granted by a user identity management system. The availability of services is managed by an M&S services management system that facilitates the delivery, versioning, testing, consumption, termination and disposal of services as shown in Figure 2. The system architecture involves the use of a hybrid cloud where the user can mix use of physical machines, virtual machines and containers (Figure 2) by means of a Platform as a Service solution based on OpenStack installed inside a VMware cluster. OCEAN is expected to provide C2SIM as a Service for experimental purposes by the end of 2019.

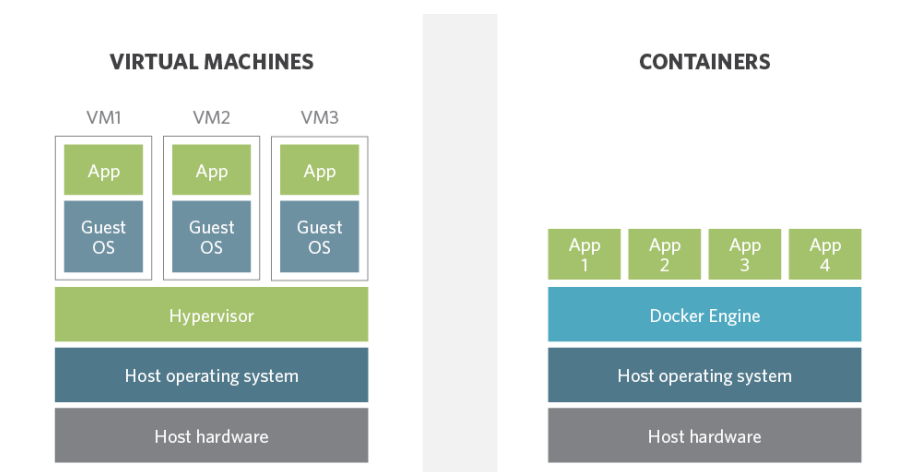


Figure 2: OCEAN architecture

4.0 TRANSITIONING C2SIM SANDBOX TO MSCOE

Under the MSG-145 activity, an integration and testing environment called *C2SIM Sandbox* was developed by George Mason University (GMU) to provide a full C2SIM capability, available via a virtual private network (VPN) by remote desktop technology, allowing national teams to test and demonstrate any combination of C2 systems, simulation systems, and servers [11].

The C2SIM Sandbox is composed from:

- the BMLC2GUI editor as a surrogate for C2;
- the VT-MÄK commercial combat simulation VR-Forces;
- the C2SIM Reference Implementation Server, open source software developed for the SISO C2SIM standards effort, featuring interoperation with MSDL, C-BML and IBML09 message specifications through schema translation;
- virtual/remote desktop via Web browser, available commercially in open source Apache Guacamole;
- audio/video/whiteboard/chat conferencing open source system Jitsi as a collaboration/conferencing component;
- an open source scheduler for managing shared access to the Sandbox.

The C2SIM Sandbox provides a continually available environment by Virtual Private Network to national teams to test and demonstrate C2SIM. In particular it allows C2SIM testing in the following forms:

- Test C2 with Sandbox Server and Simulation
- Test Server with Sandbox C2 and Simulation
- Test Simulation with Sandbox C2 and Server
- Test C2-Simulation Coalitions with the Server
- Distributed configurations of all sorts

The C2SIM Sandbox has been via Internet VPN from the GMU C4I and Cyber Center since 2017. By the end of the 2019 it will be deployed also at MSCOE and at least part of it will be available at MSCOE as an MSaaS container in the OCEAN platform implementing the C2SIM as a Service concept. Migration of the C2SIM Sandbox to MSCOE is part of the completion of the MSG-145 technical activity handover to NATO, to allow C2SIM testing and experimental use to continue towards a more widespread operational C2SIM adoption.

5.0 CYBER EFFECTS EMULATION USING C2SIM

There are two general areas of training for cyber security: (1) training specialized to cyber operations and (2) regular military operational training that applies to a cyber-active environment. The C2SIM Reference Implement Server supports to the latter, which is quite important because military forces must be prepared to function effectively in a cyber-active environment. The GMU C4I & Cyber Center's latest work [8] makes it possible to apply to C2SIM messages many of the effects of cyber and electronic warfare attacks to operational training. This is done by modifying the C2 messages that flow through the C2SIM server, as shown in Figure 3.

The significant difference between Figure 1 and Figure 3 is the addition of a cyber effects editor and an exercise driver that work together to impose cyberspace electromagnetic activities (CEMA effects) on the C2 message stream, creating the effect of a cyber-active environment. While this idea is not new, its impact can be greatly expanded when employed in a standards-based coalition environment. In previous implementations of this concept, it was not possible to emulate cyber effects in associated C2 systems or in the supporting networks of various members of a coalition of such systems operating under the MSDDL/C-BML standards, without modifying all C2 and simulation systems involved.

By imposing cyber effects in the simulation, it is possible to achieve a wide range of training stimuli across a coalition without compromising any C2 systems or adding functionality to simulation systems. This can be achieved in environments as simple as a single pairing of C2 and simulation, more complex environments such as in joint training with each component having its own C2 system and simulation, or the even more complex environment in a coalition where several nations are involved, each with one or more C2 systems and simulations. An early test of these concepts was completed by MSG-145 in CWIX 2019 [3].

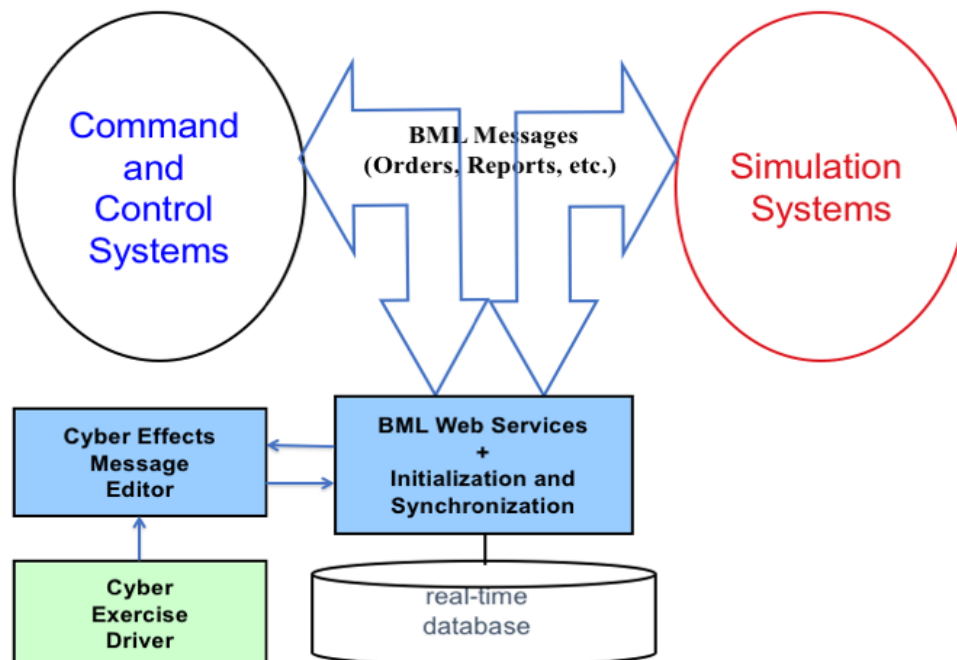


Figure 3: C2SIM architecture with cyber effects imposed on C2 messages

6.0 EXPANDING C2SIM: THE AUTONOMOUS SYSTEMS EXTENSION

C2SIM is intended to provide a standard for expressing and exchanging Command and Control (C2) information between C2 and robotic and autonomous systems (RAS) in any context. MSCOE has concentrated its efforts on such systems in the coalition context, developing for MSG-145 the use case of the Autonomous Systems (AS). The Autonomous Systems eXtension (ASX) was developed and tested, adding another layer of data classes on top of C2SIM core+SMX+LOX addressing the specificity of the AS domain.

The AS use case was developed by MSCOE in the framework of their “Research on Robotics for Concept and Capability Development” (R2CD2) project, whose aims were to concentrate on: the interaction between Simulated UAxS and real C2 systems; studying the Unmanned Autonomous Systems (UAxS) employment in a megacity of the future (for land and air domains); and Decision Making support for robots using Artificial Intelligence (AI), implementing this Autonomous Function in an external system or in the robotic platforms depending on their level of autonomy. To do this, MSCOE reused the Level of Autonomy (LoA) concept from NATO Allied Command for Transformation (ACT) and the “Archaria” urban model of a megacity of the future from ACT Urbanization Project (UP).

The process for the ASX definition started with the search for its requirements, using a scenario-based methodology delineated in the SISO Guidelines for Scenario Development (GSD) [12]. An operational scenario was designed, based on the simulation objects of the R2CD2 project. Then a conceptual scenario was derived from it, describing the actors, their interactions and flow of actions formally, making use of the NATO Architectural Framework (NAF). Most important, the information exchange requirements (IER) of the scenario were set. The IER was the main source for requirements of new data classes necessary for orders, reports and initialization information to execute the scenario and to build the ASX.

The second step involved the definition of the ASX ontology based on the found requirements. For this goal the Protégé software [13] was employed, extending the objects, data and their properties contained in the basement made by the core+SMX+LOX ontology. The SISO C2SIM PDG guidelines were followed, avoiding repetitions and definitions of elements not peculiar to AS domain. After adding the ASX ontology to this, the standard SISO C2SIM XSLT was applied deriving the ASX XML schema. When the ASX schema was tested in the execution of a scenario, it was demonstrated to be possible to build all the necessary C2SIM messages. It is noteworthy that the described process for schema development is a dynamic one; it automatically includes any changes in the core+SMX+LOX schema, based on the scenario requirements), and also modifications in the ASX ontology, when the schema is produced. Figure 4 summarizes the process.

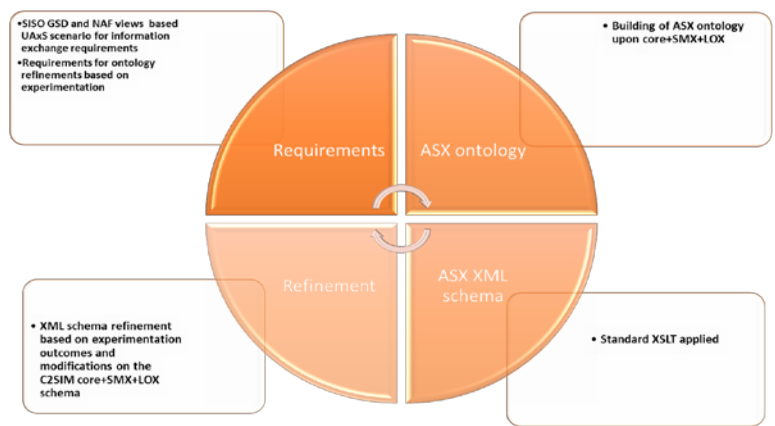


Figure 4: ASX development process

7.0 CONCLUSION: C2SIM IN OPERATION

The work of NATO MSG-145 and SISO C2SIM PDG has developed a new tool for coalition training, course of action analysis, and mission rehearsal and confirmed its readiness for use. The GMU C4I and Cyber Center and NATO MSCOE have advanced these activities by collaboratively building and supporting open source software: the BMLC2GUI Editor and the C2SIM Reference Implementation Server, that have made this implementation and testing much more productive. GMU also has developed a prototype cyber effects capability for the server and MSCOE has developed and prototyped a forward-looking Asynchronous Systems Extension for C2SIM. These systems show great promise for continuing to accelerate development and deployment of C2SIM for operational use in NATO nations' C2 and simulation systems.

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