NORTH ATLANTIC TREATY ORGANIZATION

SCIENCE AND TECHNOLOGY ORGANIZATION

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STO TECHNICAL REPORT **TR-HFM-247**

Human-Autonomy Teaming: Supporting Dynamically Adjustable Collaboration

(Équipe humain-autonomie : soutien d'une collaboration ajustable)

This Report documents the findings of Task Group HFM-247 (2014 – 2019), which explored the rapidly developing area of Human-Autonomy Teaming (HAT).

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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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List of Acronyms

A&MM	Autonomy and Mission Management
ACFP	Autonomous Constrained Flight Planner
ACL	Aircraft Control List
AFFOC	Air Force Future Operating Concept
AI	Artificial Intelligence
AM	Asset Manager
AMS	Autonomy and Mission Systems
AMSL	Above Mean Sea Level
ANOVA	ANalysis Of VAriance
ANR	French National Research Agency
AP	Adaptability Proficiency
ARL	U.S. Army Research Laboratory
ARPI	Adaptive Collaborative/Control Technologies
ASD/R&E	Assistant Secretary of Defence for Research and Engineering
ASM	Autonomous Squad Member
ASUR	Autonomous Systems Underpinning Research
ATC	Air Traffic Control
ATIS	Automatic Transmitter Identification System
AV	Autonomous Vehicle
BDI	Beliefs, Desires, Intentions
C2	Command and Control
C2-MM	Command and Control – Mission Management
CAPTEAM	Collaborative Adaptability Proficiency Test Evaluation Assessment Methodology
CAS	Close Air Support
CASEVAC	Casualty Evacuation
CCTA	Crew Coordination and Task Awareness
CDO	Cognitive Domain Ontology
CECEP	Cognitively Enhanced Complex Event Processor
CMM	Capability Maturity Model
CMRE	Centre for Maritime Research and Experimentation
CMU	Carnegie Mellon University
COA	Course of Action
COFOR	Common Frame of Reference
CogA	Cognitive Agent
COI	Community Of Interest
COMAO	COMposite Air Operations
COMINT	COMmunications Intelligence
COMPACT	Configurable Operating Model Policy for Automation and Control of Tasks
CONOPS	CONcept of OPerationS
ConvT	Conventional Tools
COWORK2	COmmunication and WORKload analyses to study COllective WORK of fighter pilots
CRM	Crew Resource Management
CSE	Cognitive Systems Engineering
CT	Collective Task
CV&V	Collaborative Validation and Verification
CWS	Common Work Space

DAMM	Dynamic Air Mission Management
DARPA	Defence Advanced Research Projects Agency
DAY17	DAYton 2017
DCF	Defence Capability Framework
DFG	Deutsche ForschungsGesellschaft
DGA	French Defence Procurement Agency
DLoD	Defence Lines of Development
DoD	Department of Defence
DSB	Defense Science Board
DSTL	Defence Science and Technology Laboratory
DTD	Double-Tracking Device
EBO	Effects Based Operations
EF	Enemy Forces
EOB	Electronic Order of Battle
EPOG	Eye-Point-Of-Gaze
ETA	Estimated Time of Arrival
ETE	Estimated Time Enroute
EVACS	EVACuation Scenarios
FAC	Fast Attack Craft
FIA	Fast Inshore Attack
FIAC	Fast Inshore Attack Craft
FLSC	Swedish Air Force Combat Simulation Centre
FOB	Forward Operating Base
FOI	Swedish Defence Research Agency
FSB	Free Saxonian Brotherhood
FSS	Division for Defence and Security, Systems and Technology
GER	GERmany
GoD	Government of Dragonia
GPCV	Goals (G), Plans (P), Constraints/Stipulations (C), and/or Values (V)
GPS	Global Positioning System
GUI	Graphical User Interface
HAC	Hierarchical Ascendant Clustering
HASIC	Human/Autonomous System Interaction and Collaboration
HAT	Human-Autonomy Teaming
HATTEAM	Human Autonomy Teaming Test Evaluation Assessment Methodology
HeR	Heterarchical Relationship
HF	Human Factors
HFM	Human Factors and Medicine
HiR	Hierarchical Relationship
HLOC	High Level Operational Concept
HMA	Helicopter Maritime Attack
HMI	Human-Machine Interface
HR	Heart Rate
HT	Human Teaming
HTN	Hierarchical Task Network
HUD	Head-Up Display
HUMINT	HUman INTelligence
HumW	Human Worker
IA	Intelligent Agent
IED	Improvised Explosive Device
IER	Information Exchange Requirements

IFS	Institute of Flight Systems
IMPACT	Intelligent Multi-UxV Planner with Adaptive Collaborative/Control Technologies
ISR	Intelligence, Surveillance and Reconnaissance
ISTAR	Intelligence, Surveillance, Target Acquisition and Reconnaissance
IT	Information Technology
LoA	Level of Automation
LVC	Live Virtual Constructive
M	Mean value
MC	Mission Commander
MCDM	Mission Critical Decision Making
MDCS	Multi Domain Control Station
METAR	METeorological Aerodrome Report
MHC	Meaningful Human Control
MM	Mission Monitor
MoD	Ministry of Defence
MODAF	MoD's Architecture Framework
MOE	Measures Of Effectiveness
MOP	Measures Of Performance
MUMT	Manned UnManned Teaming
NASA	National Aerospace and Space Administration
NATO	North Atlantic Treaty Organization
NDZ	Northern Disputed Zone
NIAG	NATO Industrial Advisory Group Study
NIWC Pac	Naval Information Warfare Center Pacific
OP	Ontology design Patterns
OPCON	Operational Control
OUAS	Operational Unmanned Air System
P2P	Peer to Peer
PCA	Principal Component Analysis
PD	Pupil Diameter
PDDL	Planning Domain Definition Language
PeCoX	Perceptual-Cognitive eXplanation
PID	Positive IDentification
PMS	Probability of Mission Success
PolMan	Policy Management
Q&A	Questioning and Answering
R&D	Research and Development
RAM	Random Anti-terror Measures
RCO	Rescued Crew Operations
ROE	Rules Of Engagement
RP	Route Planner
RR	Respiratory Rate
RT	Reaction Time
S&T	Science and Technology
SA	Situation Awareness
SAGAT	Situation Awareness coGnitive and AffecTive load

SAT	Situation Awareness-based agent Transparency
SATLAOP	Self-Aware Trustworthiness Levels and Assurance with Operational Policy
SATLID	Self-Aware Trustworthiness Levels and Information Dissemination
SC	Skin Conductance
sCE	situated Cognitive Engineering
SE	Synthetic Environment
SEM, SD	Standard Error Measure
SME	Subject Matter Expert
SO	Sensor Operator
SPAWAR	SPAce and Naval WARfare Systems Command
SUS	System Usability Scale
T&E	Test and Evaluation
TA	Technical Activity
TACON	TActical CONtrol
TAPAS	Techniques d'Analyse du Partage d'Autorité des Systèmes de Systèmes
TER	Technical Evaluation Report
TG	Task Group
TIC	Troops In Contact
TNO	Netherlands Organisation of Applied Research
TOC	Test Operator Console
TP	Team design Patterns
TRADR	Long-Term Human-Robot Teaming for Disaster Response (European project)
TSA	Team Situation Awareness
TSD	Traffic Situation Display
TTC	Time-To-Collision
TTPs	Tactical Techniques and Procedures
TUAS	Tactical Unmanned Air System
UAS	Unmanned Air Systems
UAV	Unmanned Air Vehicle
UCAV	Unmanned Combat Air Vehicle
UGV	Unmanned Ground Vehicle
UK MoD	United Kingdom Ministry of Defence
UML	Unified Modelling Language
UMV	Unmanned Military Vehicle
US	United States (of America)
UUV	Unmanned Underwater Vehicle
UV	Unmanned Vehicle
UxAS	Unmanned Systems Autonomy Services
UxV	Unmanned Vehicle
VACP	Virginia Association of Chiefs of Police
VBIED	Vehicle Bourne Improvised Explosive Device
WA	Work Agreement
WEnv	Work Environment
WITS	Wildcat ISTAR Teaming for Strike
WObj	Work Objective
WPout	Work Process Output
WProc	Work Process
Wsys	Work system

Glossary

AMASE	UxV simulator
CONUS	USA border map
CPLEX	IBM modelling tool
LASSA	Command and control of systems of systems with autonomous capabilities
MUM-T	Universität der Bundeswehr simulation environment
NASA-TLX	Workload metric
SCP	Pilot's interruption

HFM-247 Membership List

CO-CHAIRS

Dr. Mark DRAPER (Chair)
US Air Force Research Laboratory
UNITED STATES
Email: mark.draper.2@us.af.mil

Prof. Dr. Mark NEERINCX (Deputy Chair)
TNO
NETHERLANDS
Email: mark.neerincx@tno.nl

MEMBERS

Mr. Marcel BALTZER
Fraunhofer FKIE
GERMANY
Email: marcel.baltzer@fkie.fraunhofer.de

Mr. Mike BARNES
RDRL-HRM-AY US Army Research Laboratory
UNITED STATES
Email: michael.j.barnes.civ@mail.mil

Dr. Eva BESADA-PORTAS
Complutense University of Madrid
SPAIN
Email: ebesada@ucm.es

Dr. Jessie CHEN
US Army Research Laboratory
UNITED STATES
Email: jessie.chen@us.army.mil

Prof. Dr. Gilles COPPIN
IMT Atlantique / Lab_STICC
FRANCE
Email: gilles.coppin@telecom-bretagne.eu

Dr. Diana DONATH
Universität der Bundeswehr München
GERMANY
Email: diana.donath@unibw.de

Mr. Antony GRABHAM
DSTL
UNITED KINGDOM
Email: apgrabham@dstl.gov.uk

Prof. Dr. Annette KLUGE
Ruhr-Universität Bochum
GERMANY
Email: Annette.Kluge@rub.de

Dr. Doug LANGE
Naval Information Warfare Center
UNITED STATES
Email: doug.lange@navy.mil

Dr. Chris MILLER
Smart Information Flow Technology
UNITED STATES
Email: cmiller@sift.net

Mr. Timo RÖHLING
Fraunhofer FKIE
GERMANY
Email: timo.roehling@fkie.fraunhofer.de

Prof. Dr. Axel SCHULTE
Universität der Bundeswehr München
GERMANY
Email: Axel.Schulte@unibw.de

Mr. R. Jay SHIVELY
NASA Ames Research Center
UNITED STATES
Email: robert.j.shively@nasa.gov

Mr. Robert TAYLOR
DSTL
UNITED KINGDOM
Email: rmtaylor@dstl.gov.uk

Dr. Leo VAN BREDA
TNO
NETHERLANDS
Email: leo.vanbreda@tno.nl

Dr. Rogier WOLTJER
Swedish Defence Research Agency FOI
SWEDEN
Email: rogier.woltjer@foi.se

ADDITIONAL CONTRIBUTORS

Mr. Timothy BARRY
Ball Aerospace
UNITED STATES
Email: timothy.barry.ctr@us.af.mil

Ms. Helen KEIRL
DSTL
UNITED KINGDOM
Email: hjkeirl@mail.dstl.gov.uk

Prof. Dr. Christine CHAUVIN
Université Bretagne Sud
FRANCE
Email: christine.chauvin@univ-ubs.fr

Mr. Maris VIKMANIS
US Air Force Research Laboratory
UNITED STATES
Email: Not Available

Dr. Hubert DUCHATELLE
DGA / UM ACE
FRANCE
Email: hubert.duchatelle@intradef.gouv.fr

Human-Autonomy Teaming: Supporting Dynamically Adjustable Collaboration

(STO-TR-HFM-247)

Executive Summary

Ongoing evolution of uninhabited systems and the interconnecting agent and cloud technologies reveal a rapid blurring of boundaries between the roles of humans and machines as well as the difference between the notions of uninhabited systems and other automated processes. In the future we need to focus less on supervising uninhabited systems and more on the multi-faceted, collaborative and reciprocal interaction between human and automated processes. Effective human-automation teaming technologies will enable autonomous systems to operate robustly in hazardous environments, support the tempo of rapid operations, or operate around and interact with humans, manned platforms, and other autonomous systems in highly constrained and chaotic environments.

Given the evolving roles of human and autonomous agents, NATO should strive toward flexible, adjustable and trustworthy automation that is being operated under user sovereignty. Research Task Group (RTG) HFM-247 explored the rapidly developing area of human-autonomy teaming. This RTG consisted of 20 dedicated scientists representing seven NATO nations. HFM-247 identified and demonstrated successful teaming methodologies and interface design practices that allow for shared situation awareness of task and environment, bi-directional understanding of intent, dynamic work distribution, and effective human-autonomy mission collaboration. The ultimate goal of this research activity is to increase the effectiveness of NATO operations through flexible and robust human-autonomy teams.

HFM-247 took a structured approach to studying Human-Autonomy Teaming (HAT) that allowed for creative explorations in select areas. The group began by establishing an initial list of human-autonomy teaming research challenges which was revisited and refined at the end of the effort, based upon knowledge gained over the lifespan of the group. The group first reviewed the literature of Human-Human Teaming (HHT) to identify lessons learned, guidelines, and metrics that might be applicable to HAT. This effort proved very informative for understanding the factors that most influence team dynamics. This Human-Human Teaming investigation also allowed the group to identify how HAT is different with unique challenges that might arise.

In order to stimulate enhanced interactions and collaboration within the group, each participating nation identified at least one HAT-related Technical Activity (TA) being conducted within that nation which served as that team member's 'contribution' to the group. These TAs represented significant ongoing HAT-related research or analyses that were tracked by the TG over the group's lifespan. A total of 10 TAs were identified across the seven nations and mapped to the HAT research challenges in order to identify similar research objectives and to inspire potential collaborations. This report summarizes these activities with the key accomplishments and lessons learned.

This RTG also addressed the very real difficulties associated with generalizing HAT solutions from one application to another by conducting a novel exploration of HAT design patterns. The application of design patterns has proven to be successful in the human-computer interaction and software engineering domains, so the group examined the possibility of leveraging this concept for use in HAT applications, i.e., to provide a common structure and vocabulary for relating each other's HAT artifacts. This report documents the

standardization of nomenclature describing highly automated human-machine systems along with top-level reoccurring problems faced in HAT applications, and then proposes a few candidate HAT solutions that might serve as design pattern instantiations. This promising effort requires more research before a final judgement can be made as to the utility of this approach. However, this report describes the initial motivation and approach taken as well as some candidate patterns for continued and more rigorous assessment.

HFM-247 successfully addressed a variety of important issues such as agreement on a common system-level framework pattern approach, HAT performance metrics, and possible solutions focused on dialog management, working agreements, transparency, and explicit intent communication. Through the TAs, the RTG also concentrated on the identification and demonstration of successful HAT applications, methodologies and design practices for HAT. However, this area is complex, and there are still significant challenges to overcome before true HAT can be achieved across NATO applications. As discussed further in the report, the following areas of research are suggested for further focus and development:

1) Meaningful human control: how to establish and maintain across all AI systems;
2) Team design patterns for dynamic evolving behaviors;
3) Continuous trust-calibration for proper reliance on automation;
4) Scope enlargement to cover all relevant teaming structures and characteristics;
5) Explainable AI in human-agent teamwork; and
6) Evolving hybrid intelligence by co-learning.

Équipe humain-autonomie : soutien d'une collaboration ajustable

(STO-TR-HFM-247)

Synthèse

L'évolution actuelle des systèmes sans pilote et les technologies de cloud et d'agent d'interconnexion brouillent rapidement, d'une part, la frontière entre le rôle de l'homme et celui de la machine et d'autre part, la différence entre la notion de systèmes sans pilote et celle d'autres processus automatisés. À l'avenir, nous devrons nous concentrer moins sur la supervision des systèmes sans pilote et plus sur les interactions multiformes, collaboratives et réciproques entre l'humain et les processus automatisés. Les technologies constituant des équipes réelles entre humains et automates permettront aux systèmes autonomes de fonctionner de manière robuste dans les environnements dangereux, de soutenir le rythme des opérations rapides ou de fonctionner autour et d'interagir avec les humains, les plateformes avec pilote et les autres systèmes autonomes dans des environnements chaotiques à fortes contraintes.

Étant donné l'évolution du rôle des humains et des agents autonomes, l'OTAN devrait s'efforcer de parvenir à une automatisation souple, ajustable et digne de confiance, exploitée souverainement par l'utilisateur. Le groupe de recherche (RTG) HFM-247 a étudié le domaine en plein essor des équipes humain-autonomie. Ce RTG se composait de 20 scientifiques spécialisés représentant sept pays de l'OTAN. Le HFM-247 a identifié et fait la démonstration de méthodologies d'équipe et de pratiques de conception d'interface couronnées de succès, qui permettent une connaissance partagée de la tâche et de l'environnement, une compréhension bidirectionnelle de l'intention, une répartition dynamique du travail et une collaboration humain-autonomie efficace en mission. Le but ultime de cette activité de recherche est d'accroître l'efficacité des opérations de l'OTAN grâce à des équipes humain-autonomie souples et robustes.

Le HFM-247 a adopté une démarche structurée de l'étude des équipes humain-autonomie (HAT, Human-Autonomy Teaming), qui a permis des explorations créatives dans certains domaines. Le groupe a commencé par établir une liste initiale de défis de recherche sur les équipes humain-autonomie, qui a été révisée et affinée à la fin, à partir des connaissances acquises pendant les travaux du groupe. Le groupe a tout d'abord passé en revue la littérature sur les équipes humain-humain (HHT, Human-Human Teaming) pour en identifier les enseignements, les principes directeurs et les indicateurs applicables aux HAT. Ce travail s'est révélé très utile pour comprendre les facteurs qui influencent le plus la dynamique d'équipe. Cette enquête sur les équipes humain-humain a également permis au groupe de déterminer la spécificité des HAT et les questions uniques susceptibles de se poser.

Afin de stimuler les interactions et la collaboration au sein du groupe, chaque pays participant a identifié au moins une activité technique (TA) liée aux HAT menée en son sein, qui a constitué la « contribution » de ce pays au groupe. Ces TA étaient des recherches en cours ou des analyses liées aux HAT et le RTG les a suivies tout au long de sa durée de vie. Au total, dix TA ont été identifiées parmi les sept pays et mises en correspondance avec les défis de la recherche sur les HAT, afin d'identifier les objectifs de recherche similaires et d'inspirer de potentielles collaborations. Le présent rapport résume ces activités, avec les résultats essentiels et les enseignements.

Ce RTG a également traité des difficultés bien réelles associées à la généralisation des solutions HAT d'une application à l'autre, en étudiant de manière inédite les schémas de conception des HAT. L'application

de schémas de conception s'étant révélée efficace dans les domaines de l'interaction humain-ordinateur et de l'ingénierie des logiciels, le groupe a examiné la possibilité d'exploiter ce concept dans les applications HAT, autrement dit, pour fournir une structure et un vocabulaire communs servant à relier entre eux les artéfacts HAT des partenaires. Le présent rapport documente la normalisation de la nomenclature décrivant des systèmes humain-machine extrêmement automatisés, ainsi que les problèmes récurrents de haut niveau rencontrés dans les applications HAT, puis propose quelques solutions HAT candidates pouvant servir d'instanciations de schéma de conception. Ces travaux prometteurs nécessitent plus de recherches avant que leur utilité puisse être établie. Cependant, le présent rapport décrit la motivation initiale et l'approche adoptée, ainsi que quelques schémas candidats pour une évaluation continue et plus rigoureuse.

Le HFM-247 a traité avec succès diverses questions importantes, telles que l'accord sur une approche commune du schéma-cadre au niveau du système, les indicateurs de performance HAT et les solutions possibles axées sur la gestion du dialogue, les accords de travail, la transparence et la communication explicite de l'intention. À travers les TA, le RTG s'est également concentré sur l'identification et la démonstration d'applications HAT, de méthodologies et de pratiques de conception pour les HAT. Toutefois, ce domaine est complexe et il reste de grands obstacles à surmonter avant de parvenir à une véritable HAT dans les applications de l'OTAN. Comme en discute le rapport, nous suggérons les domaines de recherche suivants :

1) Contrôle humain sensé : comment l'établir et le maintenir dans tous les systèmes d'intelligence artificielle ;
2) Schémas de conception des équipes pour l'évolution dynamique des comportements ;
3) Étalonnage continu de la confiance pour une confiance adéquate dans l'automatisation ;
4) Élargissement du champ d'application à toutes les structures et caractéristiques pertinentes des équipes ;
5) IA explicable dans le travail d'équipe humain-agent ;
6) Évolution de l'intelligence hybride par le co-apprentissage.

Chapter 1 – INTRODUCTION

Mark H Draper
Air Force Research Laboratory
UNITED STATES

Mark A. Neerincx
TNO
THE NETHERLANDS

1.1 OVERVIEW AND SCOPE

Based on progress in robotics, artificial intelligence and human performance modelling, human-agent-robot teamwork systems are being developed and tested in which humans and (semi-)autonomous agents dynamically adjust and cooperate to accomplish a joint objective. In these systems, team members' responsibilities and commitments are managed such that the human and automation jointly enhance performance and manage contingencies. Dynamically adjustable autonomous behaviors and supporting control architectures are critical to meet the many different contexts envisioned for these systems. Future autonomous systems, whether they be Unmanned Vehicles (UVs) or autonomous virtual (software) agents, may be considered partners or even team members where tasks are adaptively re-allocated between operator and autonomous agents. The policies (e.g., authorities and obligations) for the situated work organization are tailored to the operational context by the dynamic setting of working agreements (e.g., the parameters and thresholds for dynamic task re-allocation) to maximize mission effectiveness. Adaptive work distribution and coordination are facilitated by sharing knowledge on task progress and the states of human and automation actors (e.g., intentions, abilities, momentary resources). User modelling methods support continuous monitoring, interpretation and learning of team members' states (e.g., workload), skills and performance.

Ongoing evolution of UVs and the interconnecting agent and cloud technologies reveal a rapid blurring of the boundaries between the roles of humans and machines as well as the difference between the notions of uninhabited systems and other automated processes. In the future we need to focus less on supervising uninhabited systems and more on the multi-faceted, collaborative and reciprocal interaction between human and automated processes. Given the rapid technological developments regarding increasingly adaptive autonomous agents, a strong and combined effort of NATO countries is essential to resolve the issues that arise when humans interact and collaborate with such agents in critical and complex missions. Effective human-automation teaming technologies will enable autonomous systems to operate robustly in hazardous environments, support the tempo of rapid operations, or operate around and interact with humans, manned platforms, and other autonomous systems in highly constrained and chaotic environments. Human factors design guidelines will have the greatest impact if they are identified early, before NATO design and procurement of highly collaborative autonomous systems occur. Additionally, standard operator interface design guidelines associated with the initiation, monitoring, and collaboration with autonomous systems need to be identified to facilitate interoperability across NATO. Further, a comprehensive set of methods and metrics has to be gained for sound and feasible evaluations of the evolving human-agent collaborations. The ultimate goal of the efforts surrounding this Task Group (TG) is to increase the effectiveness of NATO operations through flexible and robust human-autonomy teams.

1.2 TASK GROUP MEMBERSHIP

This task group consisted of 20 dedicated scientists representing seven NATO nations: France, Germany, the Netherlands, Spain, Sweden, United Kingdom, and the United States. The team membership remained mostly stable throughout the TG lifespan with many members having extensive research experience in this area.

1.3 TASK GROUP OBJECTIVES

Given the evolving roles of human and autonomous agents, NATO should strive toward flexible, adjustable and trustworthy automation that is being operated under user sovereignty. Task Group HFM-247 explored the rapidly developing area of human-autonomy teaming. It directly leveraged RTG HFM-170 [1] and HFM-217 [2] which developed a framework for supervisory control of human robotic systems and leveraged the development of 15 emerging technologies across 8 NATO nations. The Technical Evaluation Report (TER) HFM-217 pointed out two main sets of recommendations drawn from the Prague workshop:

1) The first recommendation is that models need to be developed and selected that can support the human factors engineers balancing act of deciding which type of task distribution in controlling multiple uninhabited vehicles best matches the real-world drivers of the specific application under consideration. A model like that could also be instrumental in providing consistency in user interface design decisions within NATO.
2) The second recommendation is based on the observation that the ongoing evolution of uninhabited systems reveals a rapid blurring of the boundaries between the roles of humans and machines as well as the difference between the notions of uninhabited systems and other automated process. Simply put, in the future we need not focus much more on supervising uninhabited systems, but rather on the multi-faceted and reciprocal interaction between human and increasingly intelligent automated processes. That a particular system is uninhabited will be a disappearing notion. What we need to have is flexible/adjustable, trustworthy automation being operated under user sovereignty. This will likely require not just intense collaboration but potentially even a merge of the field of human factors engineering with other engineering fields such as process automation and computer science.

Building off the acquired knowledge, the current TG HFM-247 identified and demonstrated successful teaming methodologies and interface design practices that allow for shared Situation Awareness (SA) of task and environment, bi-directional understanding of intent, dynamic work distribution, and effective human-autonomy mission collaboration.

Many related areas of research were explored within this task group. Examples include:

- Adjustable and adaptive autonomous systems;
- Authority sharing concepts;
- Manned-unmanned team situation awareness and performance;
- Bi-directional conveyance of intent;
- Goal-based control methods;
- Human-autonomy problem solving / cooperative dialog;
- Decision support interfaces;
- Situation assessment aids, feedback of action impact;
- Predictive / look-ahead tools, anticipatory support;
- Intelligent aiding for time-critical team decision making; and
- Multi-modal interfaces, intuitive and natural language interfaces.

1.4 TASK GROUP APPROACH TO EXPLORING HUMAN-AUTONOMY TEAMING

The RTG took a structured approach to studying Human-Autonomy Teaming (HAT) that also allowed for creative explorations in select areas.

The group began by establishing an initial list of human-autonomy teaming research challenges. This list would be reconsidered and refined at the end of the Task Group, based upon knowledge gained in the area over the lifespan of the group. To assist in this process and leverage related domains, the group first reviewed the literature on human-human teaming to identify lessons learned, guidelines, and metrics that might be applicable to HAT. This led to a side-exploration of applying candidate human-human teaming metrics to an existing HAT project within the team, which created both insights and issues associated with metric utility. This human-human teaming investigation also allowed the group to identify how HAT is different with unique challenges that might arise. See Chapter 2 for a summary of this work.

Given the direction from the HFM panel for the TGs to focus on:

1) Increasing team collaborative efforts; and
2) Hosting high-fidelity Technology Activities (TAs) vs. strictly discussing lab research findings.

The team formulated the approach to facilitate these objectives. Therefore, early in the effort, each participating nation identified at least one Technical Activity (TA), which served as that team member's 'contribution' to the group as well as a basis by which to explore intra-group collaborations. These TAs represented significant ongoing HAT-related research or analyses within NATO that would be tracked by the TG over the lifespan of the group. In addition, many TG meetings focused on a particular TA, allowing for a deep dive exploration of issues, challenges and findings associated with that effort. A total of 13 TAs were identified across the seven nations with various start and end times (some continuing after the TG lifespan). The TAs were then mapped to the HAT research challenges in order to identify similar research objectives to inspire potential collaborations.

Collaboration among each of the participating nations was rated along a graduated scale (Figure 1-1). This scale defaults at 'no collaboration', which is applicable to many situations given constraints placed on programs and costs of collaboration. As collaboration level increases, the scale rises to "coordination" (information sharing, schedule coordinating, witnessing the TA), then to "cooperation" (structuring similarly focused tech demos to enhance effects, maximize information gathering, data collection) and finally to full "collaboration" (multiple NATO nations combine resources to produce a truly integrated TA). Full collaboration was achieved in a few instances within this TG and is described in Chapter 5.

For each TA, the eventual level of collaboration for each country/representative was dependent upon several variables including level of mutual research interest, availability of resources, alignment of resources, timing, value added, etc. The method for identifying and characterizing instances of collaboration is described below.

Each TA "owner" was required to complete a collaboration matrix (see Table 1-1) that conveyed how much collaboration was desired (and in what area of the TA). One dimension of the matrix consisted of 3 levels of collaboration while the other represented 3 different phases of a TA. For each TA, this completed matrix was presented along with a discussion of the TA (objectives, approach, design, etc. Some TAs resulted in few to no collaborations while other TAs had much interest from various countries.

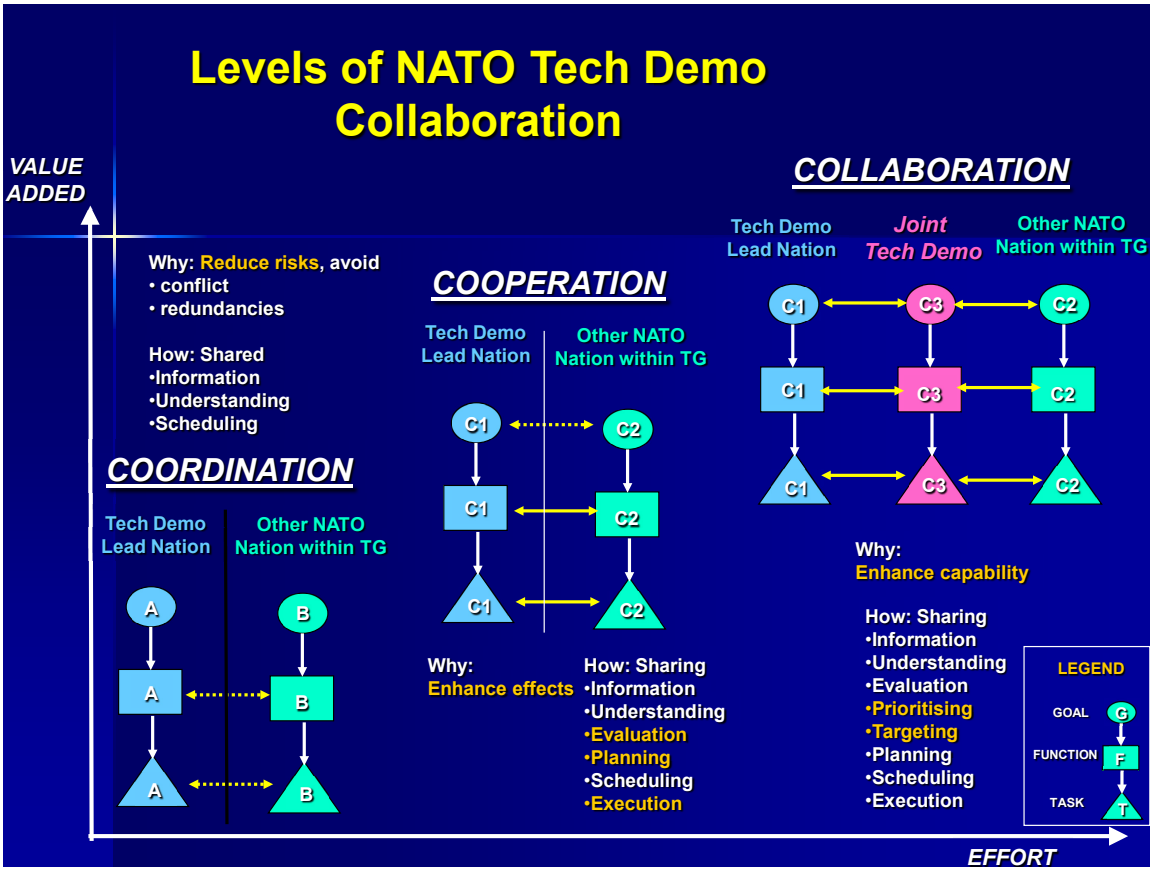

Figure 1-1: Levels of NATO Technology Activity Collaboration for HFM-247.

Table 1-1: Collaboration Matrix for Each TA.

	Planning/Design	Execution	Analysis
Communication			
Coordination			
Collaboration			

The follow-on meetings occurred approximately every 6 months, over the lifespan of the group. As much as possible, meetings centered around one or more TAs associated with the host country. The researchers presented the TA(s), invited specialists as desired, and used the available time to discuss and critique the research specifics. Contrasting approaches/concepts were also discussed.

Finally, an attempt was made to link the TAs to a unifying military relevant scenario, however that activity did not prove to be fruitful. Any exploration of HAT within NATO must understand and fully consider the military relevance of increasingly autonomous systems. Chapter 3 offers this critical connection between HAT and future military operations within NATO, which forms the foundation for continuing research in this area.

This TG also addressed the very real difficulties associated with generalizing HAT solutions from one application to another through an exploration of design patterns. Design patterns have proven to be successful in the human-computer interaction and software engineering domains, so the group decided to examine if this concept could be leveraged for use in HAT applications, i.e., to provide a common structure and vocabulary for relating each other's HAT artifacts. The core idea was to identify reoccurring problems faced in HAT applications, and then propose a few candidate HAT solutions that might serve as design pattern instantiations. This promising effort needs more research before a judgement can be made as to the utility of this approach, however Chapter 4 describes the initial motivation and approach taken as well as some candidate HAT patterns for continued assessment.

Finally, the TG identified research priorities for continued research in this important area. The group ranked a list of candidate challenges in terms of perceived importance, and the resulting list was also linked via a conceptual mapping. These priorities can be found in Chapter 6.

As a means to disseminate the results and lessons learned from this TG, a NATO symposium (HFM-RSY-300) is organized at the end of this effort. This symposium will include presentations and demonstrations of selected TAs conducted throughout the TG period.

1.5 TASK GROUP DELIVERABLES

Deliverables from HFM-247 included the following:

- Documentation of all tracked TAs (HAT technology activities) and their resultant findings/lessons learned (see Chapter 5). This product conveys knowledge of current research activities within NATO.
- A description of how HAT is similar to as well as divergent from human-human teams, based upon a review of relevant research. This product offers guidance regarding the potential leveraging of past research.
- The results of an exploration into the possibility of establishing design patterns for HAT much like has been accomplished successfully in the software development domain. This product provides new knowledge as to novel approaches to HAT design. It might be developed further towards a shared evolving knowledge base that maintains and exemplifies successful solutions.
- Priorities for future research in the area of human-autonomy teaming. This product provides informed recommendations to best direct related S&T programs.

1.6 REFERENCES

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Chapter 2 – HUMAN-AUTONOMY TEAMING (HAT)

Prof. Gilles Coppin
IMT Atlantique / Lab-STICC
FRANCE

Prof. Christine Chauvin
Université de Bretagne Sud / Lab-STICC
FRANCE

Mark H. Draper
Air Force Research Laboratory
UNITED STATES

Robert J. Shively
NASA Ames Research Center
UNITED STATES

Rogier Woltjer, PhD[1]
Swedish Air Force Combat Simulation Centre (FLSC)
SWEDEN

2.1 HUMAN TEAMS, HUMAN-AUTONOMY TEAMS

2.1.1 Introduction

Teaming is mostly a human activity and concept. It corresponds to a collective action dedicated to reach supposedly joint and shared objectives. A team is, thus, conventionally defined as a "distinguishable set of two or more people who interact dynamically, interdependently, and adaptively towards a common and valued goal/objective/mission, who have each been assigned specific roles of functions to perform, and who have a limited life-span membership" [1].

"Supposedly" is here to open to configurations where members of the collection are not even aware of a joint intent, but however contribute to reaching objectives predefined by upper-level observer. This distinction refers to the respective definition of collective intelligence vs. distributed intelligence [2]. When speaking about teaming, and when asserting it is a peculiar human activity, we suppose the team members to be aware of the joint objectives, so that a common intent may be elicited.

Let us rephrase this when considering (and playing with) the etymology of the terms: team means, among other definitions, harness animals to tug a vehicle. In past and still current main understanding, this is applicable as a metaphor to collective human actions supported by a machine or a computer: human/animals define the direction, the vehicle/computer follows and is only of limited help (in storing information and knowledge for instance). Now the "vehicle" is autonomous in the sense we know from Google Car. It has become potentially active in goal and path definition, as well as in provoking movements by itself. Humans ("animals") remain in most cases useful thanks to their perception and reasoning abilities but may even become followers instead of leaders. We thus need to extend human-human teaming concepts to human-autonomy teaming.

This document is structured along the following logics: in a first part, we describe two frameworks related to cooperation in human teams, that have already been used to consider human-machine cooperation. In a second part, we focus on key points and challenges in human teams functioning. In a third part, we try to highlight which of these key points and challenges are deeply impacted when transposing a human team towards a hybrid human-autonomy one. A last part gives some hints about the use of patterns to tackle the previous challenges.

[1] With input from the respective Technical Activity (TA) authors in Subsection 2.3.5 on TA metrics.

2.1.2 Human-Human Teaming and Cooperation

This section describes two main frameworks issued from psychology and sociology and proposing complementary taxonomies to describe cooperation configuration within teams of agents. The section is mostly inspired by Ref. [3].

2.1.2.1 A Functional Framework

Cooperation is the consequence of interdependence, which refers to "the extent to which team members cooperate and work interactively to complete a task" [4]. Interdependence generates interference, a concept borrowed from physics by Ref. [5], and used as a metaphor to apply to cooperation, that: "The effects of the action of one agent are relevant for the goals of another: i.e., they either favor the achievement or maintenance of some goals of the other (positive interference) or threaten some of them (negative interference)". As a matter of fact, in physics, the combination of waveforms can lead to their reinforcement or their degradation. In the current section, interference is deemed to have two scientific connotations – both negative and positive – although popular speech has only retained the first. Within the context of Human-Human Cooperation (HHC) within small teams, a minimal definition of cooperation focuses on interference management for task facilitation:

> *Two agents are in a cooperative situation if they meet two minimal conditions: 1) Each one strives towards goals and can interfere with the other on goals, resources, procedures, etc.; and 2) Each one tries to manage the interference to facilitate the individual activities and/or the common task when it exists.* [6]

Interference may be managed at different times, that is to say, more or less close to the action. Therefore, three levels of cooperative activities can be identified according to a gradient of anticipation:

Level 1: Action level. At this level, cooperative activities consist in locally creating, detecting, anticipating, and resolving interference. Interference creation can be positive when it consists in mutual control or cross-checking. In this case, one agent can inform another of his/her disagreement, or can give advice. For example, the non-flying pilot in an aircraft cockpit may detect an error committed by the flying pilot. By voicing that suspicion, the crew can improve its performance.

Level 2: Planning level. At this level, a Common Frame of Reference (COFOR); see Ref. [6]) is explicitly generated and maintained as a common representation of the situation. The situation includes the environment (currently referred to as Situation Awareness – SA), as well as the agents' activities. COFOR includes: common goals, common plans, and the function allocation activity. At the Action level, cooperative activities are a sub-product that implicitly feed the COFOR. An appropriate COFOR can facilitate cooperation at the Action level, preventing negative interference or enabling anticipation of it, and enabling countermeasures to be taken.

Level 3: Meta Cooperation level. In the same way that the Planning level activity can facilitate the Action level activity, the Meta Cooperation level activity can also facilitate the Planning level activity. It includes high-level knowledge that is useful to other levels, such as mental models of the other agents and of oneself. Indeed, when it is difficult to communicate with one's partner (e.g., a machine), mental models may be useful for generating the necessary COFOR so that one can anticipate the partner's intention or the action that could interfere with one's own activity. For example, by observing a surgeon's behavior, the anesthetist can infer that the operation will take longer than anticipated and thus, prepare a new injection.

These levels are distinct from the levels of abstraction defined by Ref. [7] and commonly referred to by the acronym SRK. For example, interference management at the Action level can require knowledge-based

reasoning hen the solution is not obvious, whereas the use of a partner model to select the best action can be highly implicit (sub-symbolic) and immediate.

2.1.2.2 A Structural-Functional Approach

Many structural approaches to cooperation have been developed, stressing the relational structure between agents, including, for example, hierarchical, and democratic factors. One such approach, put forward by Ref. [8], is of particular interest because it is directly relevant to the functional approach. This author mainly defined three forms of cooperation, at the same time implying function allocation and relationships (structure) between the agents. Later, Ref. [9] considered combining these basic forms in order to generate a large variety of cooperation situations.

Augmentative Cooperation. This form is justified when workload increases, creating the need to add agents with the same competencies, thus requiring some redundancy between agents.

Debative Cooperation. Within this form, there is also some redundancy between agents. Here, redundancy is not devoted to multiplying work strength, but to carrying out mutual control or cross-checking of one agent on another, sometimes using a different viewpoint to detect errors.

Integrative Cooperation. In this case, the task needs agents with different competencies, an appropriate distribution of functions, and a final integration. This form is frequent in multi-expert teams [10].

Both frameworks (the functional and the structural-functional ones) have been used to define human-machine cooperation in highly automated systems. In those systems, both agents (human and machine) must develop and maintain a common frame of reference. The development and maintenance of a shared representation of the context appear, indeed, as central elements for the reliability of a system [11]. Several authors have proposed to develop a Common Work Space (CWS) [12], [13] constituting a *physical representation* of COFOR.

In a project called AMANDA, the principle of task delegation between air traffic controllers and a technical agent was evaluated [14]. To allow agents to cooperate, a CWS was implemented in order to support cooperative activities (cf. Figure 2-1). A first experiment resulted in determining the effective contents of the CWS in the case of air traffic control. A second one showed that this CWS could support and improve cooperative activities [12] because the space problem is better defined, there is less conflict between the agents because they understand the others' decisions better, and interactions thrive on problem solving strategies.

The Schmidt taxonomy is used to distinguish the three forms of cooperative activity that can be carried out around the CWS:

- In the "debative" form, all agents supply the CWS with data and when interference occurs, they can negotiate.
- In the "integrative" form, only one agent provides data and the other takes them into account to carry out his/her activity.
- In the "augmentative" form, the agents have all the same skills but carry out different tasks, depending on the allocation that is defined.

In an autonomous system, the sole observation by the human supervisor of the technical agent's behaviors is not sufficient to lead to proper understanding of what the "vehicle" is actually doing. Ref. [15] stated that the HMI should provide a transparent representation of the different stages of the decision-making process of the machine. In order to complete the principles of CWS, they investigated the Lyons' model of human-robot "transparency".

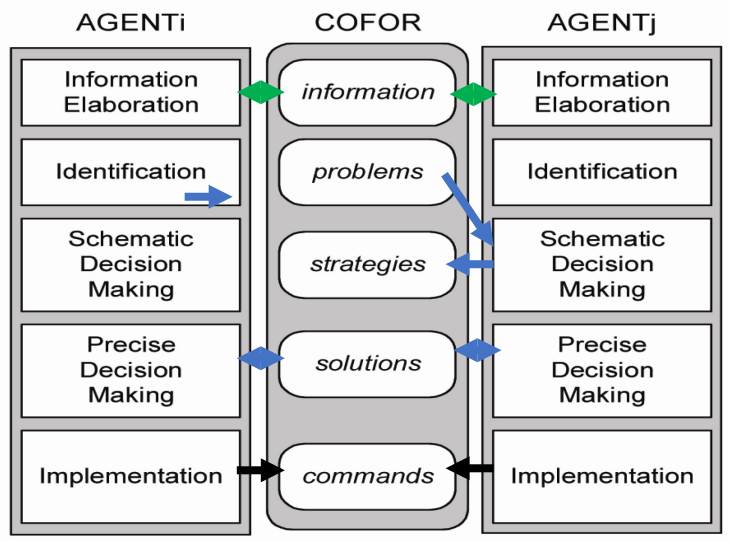

Figure 2-1: Cooperative Interaction Between Agents Through the CWS (Debative Form – Integrative Form – Augmentative Form). [14].

Ref. [16] explained that transparency between an autonomous system and a human being is one mechanism to facilitate effective interactions between humans and their robotic teammates in a dynamic environment under some conditions of uncertainty. According to this author, transparency factors involve several different models. From each model, several principles were extracted that seem to be relevant to autonomous driving. In the intentional model, Lyons argued that it is important for the user to identify the major functionalities of an autonomous system in order to fully understand its purpose.

The task model includes an understanding of a particular task, information relating to the system's goals at a given time, information relating to the system's progress in relation to those goals, information signifying an awareness of the system's capabilities, and awareness of errors.

The analytical model communicates the underlying analytical principles used by the system to make decisions.

In the environment model, the autonomous system should be capable of communicating to humans an understanding of its environment and of the temporal constraints.

A teamwork model is essential to understand the division of labor for a given task or set of tasks.

2.1.3 Human Teams' Characterization and Taxonomy

This section is based upon works of Annette Kluge, presented in San Diego during the meeting of our HFM-247 Task Group (2015) [17].

Among the main features characterizing teams' configurations, we have to focus on the following items.

2.1.3.1 Task Interdependencies

These interdependencies are usually predefined through the task model itself, but may be also dynamically tuned.

There is an obvious link between these interdependencies and the allocation of roles and functions in the team. When dealing with integrative cooperation (as described here above), specific information is to be aggregated from the different agents to reach a result so that there is a natural interdependency. But there may be various levels of description of interdependency which can be fine-grained defined in the tasks themselves.

In any case, tasks' interdependencies obviously impact the workflow and information flows between members of the team, which may contribute (or disturb) the design and dynamical maintenance of the common ground within the team.

2.1.3.2 Team Conflict Resolution

Nature of Conflict: Can be any part of Common Ground (situation, plan, goal, role and authority allocation).

Detection of Conflict: Detection may rely on observation (interpretation of other agents' intent and plans) or on direct dialog between agents (which does not fully prevent from misinterpretation). This especially needs to rely on explanations and transparency.

Resolution: Once a conflict detected, resolution strategy may be instantiated from team organization and hierarchy (one subordinate point of view must be over imposed by the leader's one) or open to negotiation, especially when dealing with uncertain information about the situation.

2.1.3.3 Coordination Strategies

In a broad sense, coordination strategies may concern the management of task interdependencies as well as the conflict resolution. Team interdependence increases [18] as team members:

- Are mutually reliant on one another for resources (e.g., information, equipment); and
- Interact during task accomplishment of collective work.

Interdependencies depend on team types and may be characterized as:

- Large informational (decision-making teams);
- High behavioral (action teams); and
- Project teams (informational + behavioral).

Team interdependence is considered as:

- Low, when performance is largely a function of individual effort;
- Moderate, when members rely on one another for some information but are able to complete a significant portion of task individually; and
- High, when there are mutual and reciprocal dependencies among all members.

Beyond aspects related to information, coordination strategies are strongly based on time management.

2.1.3.4 Progress Monitoring / Team Monitoring / Mutual Evaluation

Teaming needs to be continuously adapted according to the work progress, the states of the different team members and the changes in the environment and situation. This can be decomposed along the following three main points:

- Monitoring process towards goals;
- Team member self-monitoring; and
- Team monitoring.

2.1.3.5 Teamwork and Team Mind

Team performance and team effectiveness depend on teamwork. Team performance accounts for the outcomes of the team's actions, whereas team effectiveness is "an evaluation of the outcomes of team performance processes relative to a set of criteria" [19]. A thematic analysis led Ref. [20] to identify the main variables that seemed to affect team functioning. They suggest that five core components promote team effectiveness: team leadership, mutual performance monitoring, back-up behavior, adaptability and team orientation. Among these factors, adaptability is considered to have a direct effect on team effectiveness. It is defined as "the ability to recognize deviations from the expected action and readjust actions accordingly".

Ref. [20] also proposes that the coordinating mechanisms for effective teamwork are the development of shared mental models, achievement of mutual trust and engagement in closed-loop communication. In a more recent paper, Ref. [21] considered that closed-loop communication could be one marker for shared mental models. Effective teams are able to shift between implicit and explicit communication in response to changing environmental demands and task constraints. When engaged in explicit communication, they use closed-loop communication characterized by three features:

1) A message being initiated by the sender (A);
2) That message being received, interpreted, and acknowledged by the intended receiver (B); and
3) A follow-up by the sender ensuring that the message was received and appropriately interpreted [22].

The loop stays open when the message is not received, interpreted or acknowledged by the intended receiver.

2.1.4 Towards Human-Autonomy Teaming: Scientific and Technical Challenges

Most of previous human team protocols, challenges and features rely on implicit human abilities that are not easily transposed when dealing with autonomous systems. Beyond the aspects that have been studied for years at the level of human teams but also when dealing with more artificial frameworks such as multi-agents systems, we want to highlight here some crucial points that are still unsolved, for which some innovative solutions have been proposed within the HFM-247 Technical Activities under the form of patterns, and that could constitute a kind of scientific roadmap for the next phases.

2.1.4.1 Formal Language vs. Natural and Non-Verbal Language

As mentioned above, teaming is based on interdependencies management, coordination, conflict resolution, team mutual and self-monitoring and evaluation. These operations are often – if not always – relying on dialogs and communication within human teams. These dialogs may be standardized when dealing with critical and time-stressed systems, but they always allow to rely on human language expressiveness as well as non-verbal

signs when possible. Extending the communication towards autonomous systems raises the classical but still open question of transposing language capacities on the machine side, so as to be able to guarantee a level of communication as rich and efficient as in the case of human-human dialog.

2.1.4.2 Artificial and Human Modes of Inference, Artificial Intelligence and Explanations

As modern systems take their autonomy from learning abilities (deep learning for perception for instance), they do not mimic human cognitive processes and may become completely opaque for their users/partners. That is, the respective modes of reasoning expected to be developed by artificial autonomous systems and expert operators have a high risk not to be aligned and mutually understandable. This corresponds for instance to the current very sensitive question of explainability of deep learning. This question has obviously to be addressed when thinking about human-autonomy teaming.

2.1.4.3 Affect and Emotion Management

Human teams, especially when facing critical situations, have to take into account and manage emotional states of team members. A team leader must understand the levels of stress of the various team members and may adapt his/her strategy of team management accordingly, as well as apply some tactics dedicated to lower or smooth stress and emotions level if necessary. When a teammate happens to be an autonomous system, it has to be equipped of similar mechanisms of emotion detection and assistance to emotion coping.

2.1.4.4 Implicit Knowledge Within a Team, Team Expertise

Teams of operators may of course change and be reconfigured in time, but they progressively build knowledge both at individual and collective levels. This knowledge may often remain implicit (one can “know” about the decision style of a leader he/she already met in a previous mission, for instance) but even so, it may provoke subtle adaptations in behavior.

As classically described in knowledge management, team members may also build personal or collective expert rules as a complement to the doctrine and explicit knowledge, as any expert would do within a complex socio-technical system. These elements of knowledge have to be learned by an autonomous system when being introduced as a team mate to tune and adapt its own behaviors to the other team mates’ expertise and “style”.

2.1.4.5 Common Ground Building

Common ground consists of shared knowledge between members and may concern internal and external elements of the system: the state of the system itself (including human operators), the roles and responsibilities of each team mate, the tactical situation, etc.

Task sharing, task allocation and distributed situation assessment rely on common ground. Setting and maintaining the team common ground will thus be crucial within critical multi-operator systems. As common ground management may be easily (or naturally) set and maintained through natural dialog within human teams, it needs to be specifically processed when introducing an autonomous system within the team.

2.1.5 Human-Autonomy Teaming and Patterns

The HFM-247 especially worked on defining abstract patterns which could be considered as solutions to the main challenges related to the introduction of an artificial agent within a collective of human teams. Table 2-1

below indicates which technical challenges and which team features each of these patterns addresses. Each pattern is described in detail in the following sections of this chapter.

Table 2-1: Team Taxonomy Features, Scientific Challenges and Patterns.

	Natural Language	Modes of Inferences	Affect Management	Implicit Knowledge and Team Expertise	Common Ground
Task Interdependencies		Working agreement		Cooperative guidance and control Explicit intent communication	Dialog management Work agreement Explicit intent communication
Team Conflict Resolution	Dialog management	Transparency		Transparency Explicit intent communication	Work agreement Increasing urgency and adaptive automation
Coordination Strategies	Dialog management	Working agreement		Explicit intent communication Transparency	Increasing urgency and adaptive automation Explicit intent communication
Team Monitoring			Dialog management		Dialog management

2.2 HAT CHALLENGES

2.2.1 Overview and Scope

Although much of the focus surrounding autonomy has centered on the development of the various computational methods to achieve machine decision-making capability, an overarching challenge relates to how to interface these approaches with humans, whether these humans be operators, supervisors, teammates, maintainers, etc. It is at these touchpoints between human and autonomy that care must be given to ensure effective overall human-autonomy system performance is achieved. Therefore, it is critical to determine the major challenges associated with Human-Autonomy Teaming (HAT) so that NATO research efforts can be best directed.

Section 2.1.5 provided a nice introduction to HAT scientific and technical challenges that were directly extracted and extended from extensive human-human teaming research. These identified challenges include formal vs. natural/non-verbal language, artificial and human modes of inference and explanations, affect and emotion

management, team expertise, and maintenance of common ground. The goal of this section is to aggregate these challenges with those identified from other sources.

Several recent autonomy-related reviews/analyses have also derived lists of human-autonomy teaming challenges. The HFM-247 Team decided to review these lists and, building upon commonalities, coalesce these individual results into a single comprehensive set of challenges that reflect both the findings of these earlier groups as well as the unique judgement of our Task Group. What follows is a summary of a select subset of these existing reports on HAT challenges, followed by a detailing of an aggregated set of HAT challenges deemed critical by the HFM-247 Task Group.

2.2.2 US DoD Community of Interest Autonomy Subgroup on Human/Autonomous System Interaction and Collaboration

The Autonomy Community of Interest (COI) closely examines the US DoD's Science and Technology (S&T) investments in the enabling of autonomous systems, to include the strategic assessment of the challenges, gaps, and opportunities to the development and advancement of autonomous systems and identification of potential investments to advance or initiate critical enabling technology development. The Autonomy COI consist of four subgroups. The Human/Autonomous System Interaction and Collaboration (HASIC) subgroup, comprised of scientists from the US service laboratories, released a list of four major HAT challenges beneath a central technical challenge of "Shared perception, understanding and collaboration" [23]:

- Calibrated trust and transparency:
  - Collaboration requires understanding of and confidence in behaviors and decision making across a range of conditions. Transparency enables the person to understand what the agent has done, is doing, and will be doing, along with supporting rationale when possible.
- Common understanding and shared perception:
  - For people and agents to have shared understanding (common ground) and situational awareness, data and information must be in appropriate representations and transmittable in discernible formats and timescales. Information must be in a form readily understood by person. Recognition of relevant activity is also important.
- Human-agent communication/interaction:
  - The system must allow for fluid and natural interactions. Multiple alternative methods of control input should exist to enable the human operator to use most effective communication mode for each situation (language, gesture, touch, keyboard/mouse, joystick, etc.).
- Collaboration:
  - Transfer/hand-over of task execution and decision making between human and autonomy must be clear, graceful and flexible/adaptive. The "system" (including people and machines) must be able to dynamically adjust the level of authority and decision making based on the mission situation and relative performance. In addition, much work is needed to support dynamic joint task completion.

2.2.3 US Office of Naval Research (ONR) Science of Autonomy Workshops

The ONR Science of Autonomy program addresses critical multi-disciplinary research challenges that cut across different departments and warfighting areas/domains. This program considers different autonomous system domains (air, sea, undersea, ground) that have traditionally been somewhat separated from a Command and

Control (C2) perspective as well as multiple disciplines including control theory, artificial intelligence, human factors engineering and related fields such as biology/animal behavior/cognition, economics/management theory, cognitive science/psychology and neuroscience. Sponsored workshops over a period of years have identified many challenges associated with autonomy, with "human/unmanned system collaboration" considered as an overarching challenge [24]. Within this topic area are three component challenges:

- Improving human-autonomy function division and relationships/roles (who does what functions, and in what kind of relationship?):
  - Optimizing task and function allocation and the human-autonomy relationship.
  - Diverse human roles mapped to context and environment.
  - Joint human-autonomy systems that remain robust in dynamic environments.
  - Adaptive autonomy (dynamically changing levels of autonomy and interaction).
  - Adaptive human-autonomy interfaces.
- Improving human-autonomy interaction/communication (how should humans and autonomy best communicate?):
  - Cognitively compatible behavior during interaction.
  - Automation transparency and appropriately calibrated trust in automation.
  - Social behavior, dialog management, non-brittle cognitive models.
  - Natural interactions vs. effective-but-learnable interactions.
  - Individuals or teams of users task, shape, and redirect the capabilities and behaviors of large numbers of heterogeneous entities (100s to 1,000s to 10,000s).
  - Identification and correction of errors and support for interruption resumptions.
  - Improve human-autonomy team effectiveness, modelling teamwork and coordination behavior of effective human teammates in autonomous ones.
  - Rich, rapid exchange of information and knowledge in instances where interaction can only occur in short periods of times relative to the overall mission.
- Improving human-autonomy comprehension (how do humans and autonomy understand one another?):
  - (The autonomy's) ability to understand intent and recognize deception and actions of manned platforms, adversaries, bystanders and human team members.
  - Similar representations and reasoning mechanisms as humans or otherwise more understandable.
  - Activity recognition, computational cognitive models; perception.
  - Shared situation awareness – projection and understanding intent.
  - Representations of system state to facilitate human understanding.
  - Effectual mental model construction through appropriate metaphors and "what if?" reasoning.
  - Cognitive skills, common ground, suitable ontology, social behavior.
  - Joint learning between humans and autonomous systems.

2.2.4 Ten Challenges for Making Automation a "Team Player" in Joint Human-Agent Activity

Academia has also weighed in on the challenges associated with HAT. A particularly thoughtful paper discussed ten specific challenges for making automation a true team player [25]. As discussed in Section 2.1, this list leverages an understanding of the factors that support successful human-human teaming to inform human-autonomy interactions:

1) **Basic Compact**: To be a team player, an intelligent agent must fulfil the requirements of a Basic Compact to engage in common-grounding activities.
2) **Adequate Models**: Agents must be able to adequately model the other participants' intentions and actions vis-à-vis the joint activity's state/evolution – for example, are they having trouble? Are they on a path proceeding smoothly? What impasses have arisen? How have others adapted to disruption?
3) **Predictability:** Human-agent team members must be mutually predictable.
4) **Directability:** Agents must be easily directable.
5) **Reveal Status/Intentions:** Agents must be able to make pertinent aspects of their status and intentions obvious to their teammates.
6) **Interpreting Signals:** Agents must observe and interpret pertinent signals of status and intentions of other team members.
7) **Goal Negotiation:** Agents must be able to engage in goal negotiation.
8) **Collaboration:** Support technologies for planning and autonomy must enable a collaborative approach.
9) **Attention Management:** Agents must be able to participate in managing attention.
10) **Cost Control:** All team members must help control the costs of coordinated activity.

2.2.5 HFM-247 Derived Set of HAT Challenges

After reviewing several such lists and grouping like-minded HAT challenges, the following list of aggregated challenges emerged. This list represents a key set of challenges that must be overcome in order to enable robust, operationally ready human-autonomy teaming capabilities for future NATO operations. Note that no prioritization has been assigned to these challenges due to the highly influential role of application context. However, it is safe to assume that each of these challenges will need to be addressed across the wide range of future NATO HAT operations.

1) **Human-Autonomy Interaction/Communications**

   Communication is clearly a critical aspect of successful teaming relationships [26], [27]. Treating intelligent machines and humans as teammates raises the unique challenge of interactive communication between these disparate agents. For this interaction to be successful, first and foremost, there has to be an easily accessible communication channel with supporting ontology that allows flexible interactive communication. This is required to allow the human (or machine teammate) to effectively convey status updates, add new information into the system, and/or raise matters for attention. For example, an aircraft might be diverted by the pilot due to a medical emergency. The pilot's on-board diversion advisor (i.e., the machine teammate) may not know what airports have hospitals nearby, but the pilot may. Thus, there needs to be a way to quickly convey that information to allow the automation to bring its processing power the bear with the most contextually relevant information. Bi-directional communication

would also enable either teammate to ask about the reasoning for a decision (i.e., transparency) or ask "what if" questions. As agents become more intelligent, naturalistic communications would allow for more in-depth dialog management, negotiation, and conflict resolution to occur. Therefore, enabling intuitive human-autonomy dialog is critical for future HAT operations. The most natural form for this channel to take is speech/audition. Thus, speech recognition, speech synthesis and natural language interfaces are all major challenges for HAT.

2) Functional Division and Teaming Relationship

When performing as a team, it is important for team members to know what functions they are supposed to be performing and what functions others are performing. Problems can occur if members lose track of what functions are being performed by who – well documented as "mode awareness" issues associated with early flight management systems [28]. For HAT, an intelligent agent should clearly indicate what function it is currently performing. Dynamic allocation of functions between human and agent is also a significant challenge. The dynamic allocation of new tasking must consider many factors such as current operator workload, teammate capabilities/limitations, and current related task allocations to ensure that overall team performance is maintained or improved. If autonomy is managing this dynamic task allocation, then it must have accurate task and human performance models by which to reason over. In addition, new processes/methodologies are needed to support the handoff or sharing of existing tasks between teammates.

3) Shared Comprehension/Understanding

It has been understood for some time that in teaming situations, Team Situation Awareness (TSA) is critical to high functioning and performing teams [29]. Wellens [30] defined TSA as "the sharing of a common perspective between two or more individuals regarding current environmental events, their meaning and projected future status." This is difficult even with human-human teams, but it becomes even more challenging with HAT due to the lack of shared experience, background, knowledge, etc. Therefore, in the HAT environment it's critical to have a well-defined channel to share information. This can be in the form of a common language, ontology, or symbolic logic, but there must be a way for both agents to transfer relevant information to the other. This also assists in the maintenance of shared mental models and common ground.

Humans will have displays (visual and auditory), interactions with other agents (manned and unmanned) as well as their senses to form a complex understanding of the state of the world. Automation, on the other hand, has its sensors, inputs from some (but not all) available information sources and may not be privy to much of the transaction information that the human. Therefore, a shared mental model is required that integrates information obtained from many separate sources into a single model that allows each agent to act on behalf of similar knowledge to effectively coordinate and benefit team goals.

4) Team Decision Making

Team decision making is always a challenge, and it is especially so for HAT. Certainly, it is reasonable that certain decisions might be delegated to an autonomous teammate, either by necessity (i.e., humans cannot engage due to communication or temporal limitations) or to reduce operator workload, while other decisions may always be reserved for the human (i.e., lethal engagements). However, a key challenge here is developing an error checking capability in which both teammates (human and intelligent agent) can monitor each other's decisions and, when necessary, raise concerns before actions are executed. In addition, joint decision making can be a complex process, where humans and agents combine efforts to reach a joint decision. One example of this is when a human reviews the recommendations or courses of

action from agent teammates before deciding. There is increasing evidence that decision biases and errors can occur depending upon the nature and sequence of the situation assessment (e.g., how and when information is presented to the human) [31]. Though the underlying cognitive processes associated with these decision errors are being debated [31], it is clear that they will need to be accounted for in future HAT systems. There is also the potential for a loss of creative problem solving/solutions (whether due to complacency or other factors) when the human is always presented a limited, fixed set list of candidate courses of action or recommendations by the autonomous teammate. Therefore, an additional challenge is how best to combine human problem solving with automated recommendations to minimize unintended biases and maximize creative thinking.

5) Team Learning/Training

An interesting challenge here is that, contrary to human-automation systems, human-autonomy teams will involve learning that jointly occurs on both sides. Therefore, the question becomes, how best to train humans and autonomous agents together so that they can best learn each other's patterns, strengths and weaknesses and can evolve into more highly synergized and complementary roles/relationships as the teaming matures. Of course, this implies that the agent has an ability to dynamically perceive and assess the relevant capabilities/limitations of the human and then smartly customize its actions in response. Edmondson et al. [32] found that success in team learning was aided by the way teams were formed and how they drew on their experiences – in other words, on the teams' design and management. They found three essential characteristics of teams that learned effectively:

a) The teams were designed with learning as a priority;

b) The leaders framed challenges so that members were motivated to learn; and

c) The leaders created an environment that fostered communication and innovation.

For HAT, the mix of human and automation should be carefully chosen to take advantage of the expertise of each. Part of the motivation for learning that Edmondson et al. found was a reinvention of working relationships. This implies that training will refine working relationships, which will stimulate more learning.

6) Trust-Based Effects

Trust is a complex psychological construct that has many influencing factors [33]. For HAT, trust in automation should be calibrated in order to be properly utilized [33], [34]. When automation is trusted more than it deserves, it can lead to its misuse. When automation is trusted less than it deserves, it can lead to its disuse. The goal is proper reliance on automation/autonomy when warranted. Other researchers have discussed trust in terms of many influencing factors and several have developed conceptual models of the dynamic process that governs trust and its effect. One way that trust can be calibrated is through automation transparency: the conveyance of how and why the decisions were made by the intelligent agent. A special form of this transparency is the representation of the intelligent agent's own "self-confidence" in its planned decisions/actions. Other team members can then use this information to better calibrate trust in the system by perhaps intervening more in low self-confidence reports.

7) Team Performance/Effectiveness Metrics

This challenge focuses on the need to develop new measures that properly assess the relative quality of various HAT instantiations against different military application. Certainly, much can be leveraged from reviewing metrics associated with the evaluation of all human teams, however there may be a need to refine these metrics given the unique aspects of HAT. Team performance measurement can be

organized into three main categories: observational ratings, team self-assessment, and event-based approaches [35]. For example, the Crew Resource Management skills of pilots are evaluated with observational ratings during check rides. The observer looks for behavioral markers that indicate that a pilot has good Crew Resource Management (CRM) skills or is lacking skills. For HAT, related behavioral markers could also be used when observing human-agent interactions to assess CRM skills. Event-based approaches are more objective and can be used to measure the task performance of the human-agent team. Lastly team communication should be assessed and compared against benchmarks for optimal team performance.

2.2.6 Conclusions

Clearly there are a wide range of HAT challenges that will need to be resolved in order to maximize operational interactions with increasingly intelligent military systems. Some challenges will matter more and some less, depending upon the particular mission application and level of autonomy involved. However, all focus on properly designing the human touchpoints to these systems in order to maximize flexible, safe, and efficient operations.

2.3 HAT METRICS

2.3.1 Human-Autonomy Teaming Metrics Rationale

There are a number of reasons or purposes for measuring aspects of human-autonomy teams and their performance. Three broad reasons are described here, although these points are not exhaustive. Firstly, Human-Autonomy Teams are often designed, i.e., deliberately created or planned, or could possibly assemble in a more ad hoc fashion if interoperability requirements are fulfilled. Human-Autonomy Teams can thus (deliberately designed or in a self-organizing manner) take many functional compositions, where typically one or several human operators, with one or more associate software agents, separately or jointly supervise or control one or more unmanned platforms using various degrees of automation, behaving as a team. The suitability or fitness-for-purpose of a particular design of the constellation of the Human-Autonomy Team may thus be subject of assessment, for which metrics are needed. Measurement for this purpose can then be used in the various design stages of the Human-Autonomy Team. Moreover, measurement can help assess when particular HAT designs are fit-for-purpose, to inform tactical or strategic decisions on HAT configuration. This includes identifying patterns of which configurations typically work well in which circumstances and comparing different HAT-configurations in varying circumstances.

Secondly, when Human-Autonomy Teams are designed purposefully, with various kinds of operators either in-the-loop or on-the-loop in the situation assessment and action cycle, training of the Human-Autonomy Team is needed. To measure progress in training, the effectiveness and development of performance over time needs to be assessed using metrics.

Thirdly, adaptability of the configuration of the Human-Autonomy Team to the circumstances of the mission and its environment is a characteristic that is investigated in this working group. The configuration of human operators, associate software agents, and automated unmanned platforms then aims to be changed within a mission. In that way the team is reconfigured on the assumption that a higher fitness-for-purpose can be achieved. For the human or associate agents making the decision to reconfigure the team to be well-informed, measurements on performance or other parameters within the team are beneficial.

2.3.2 Metrics Considerations

A number of considerations for metrics on teams and teaming can be derived from Cognitive Systems Engineering (CSE) [36] and Human Factors (HF) team research [37]. Both of these traditions point to the importance of **grounding measures in theory**, as well as the need to be explicit about the **purpose of measurement**. Hollnagel and Woods [36] distinguish between theory-driven and theory-begging measurements, expressing the need to derive measurements from an explicitly articulated model of the functional phenomena providing meaning to the measurements. Rosen et al. [37] also point to the need of theory and models to inform measurement, recommending the use of domain-specific models if possible, otherwise pointing to the benefit of using generic theory on teams. There is a rather extensive literature in human factors team research describing human teams. For example, Fleishman and Zaccaro [38] describe a number of functions that are generally involved in making a team function as a team (teamwork), as opposed to tasks that are needed to be performed as part of the team's assignment (taskwork). These include functions for orientation, resource distribution, timing and pacing, response coordination, motivation, systems monitoring, and procedure maintenance [38]. As another example of a generic theorization, Salas et al. [39] include five core dimensions (team leadership, mutual performance monitoring, back-up behavior, adaptability, and team orientation) and three coordinating mechanisms (mutual trust, shared mental models, and closed-loop communication) as a framework for describing teamwork. Salas et al. [40] point to a number of cognitive functions that are usually considered to be performed by individual humans to be executed jointly by the team as a whole. A parallel can clearly be drawn from human factors team research to Human-Autonomy Teams resembling the distribution of cognitive tasks across distributed or functional human-machine systems [36], [41]. Explicit articulations of team functions and mechanisms may inform the agenda for development of HAT theory and thereby HAT metrics.

Both CSE [36] and HF team research [37] point to the recommendation for **observable phenomena** to be the focus of measurement, if possible, as there are a number of disadvantages with indirect measures such as subjective self- or observers' ratings, secondary tasks, etc. In order to distinguish between various observable phenomena, Rosen et al. point out the need to distinguish between process and outcome measures. Based on the CSE focus of how human-machine systems perform as a functional whole in a complex environment, we here add emergent properties to this list as a third category of measurement:

- (Performance) **Outcomes** Metrics:
  - Defined here as metrics that describe aspects of the outcome or output of the activity that a system performs, typically performance metrics of that activity in a certain task environment.
- **Process** Metrics:
  - Defined here as metrics that describe aspects of a series of actions or operations as part of the ongoing activity that the system performs, in a certain task environment.
- (Emergent) **Properties** Metrics:
  - Defined here as metrics that describe aspects of a system as a whole, in a certain task environment (emergent refers to the fact that these properties may only be described for the whole of the system in its task environment, not merely as a sum of its parts).

Outcomes only document the final end result of an episode of behavior that is measured, and possibly intermediate steps. However, it may be essential, depending on the theoretical base and purpose of measurement, to know more about how the team arrived at that outcome, for which process measures may be used. This distinction is analogous to sports teams competing in a match. The final score on the scoreboard provides only the final outcome, which to some extent is what matters linked to the objective (winning) but does not provide much specific information as to

how the team played, e.g., to analyze and prepare for the next match. A range of dynamic teamwork and taskwork functions, tactics and strategies come to mind here that can be described as interlinked processes. Moreover, a team can be considered to play well or even better than its opponent, but anyway loose the match in terms of final score, so that processes are relevant to analyze for team analysis and learning. In addition to this, one might ascribe emergent properties to the (e.g., sports) team in that they played in a robust way, a new way, an agile way, or a spectacular way. These kinds of assessments are not captured in the outcome and are likely a more holistic assessment of multiple interlinked processes that describe various emergent properties (again based on the theory behind these constructs). The human-autonomy teamwork preconditions of for example common ground, observability, predictability, and directability between team members [42], [43] may be considered part of these emergent properties that can only be assessed considering a number of multiple-member processes in combination with individual team member characteristics. Also, considering for example the characteristics described by Salas et al., [39], [40], the question of whether a group of units actually behaves like a team is an emergent property.

Both CSE [36] and HF team research [37] stress the need for providing measures at **multiple levels of performance**. These could simply be the individual and the team levels [37] or more intricate groupings of functional systems of humans and machines that are jointly engaged in various activities [36].

In addition, well-known scientific principles such as reliability, validity, representativeness, and the benefits of triangulation need to be considered, which are out of scope of the current discussion. Finally, both CSE [36] and HF team research [37] emphasize the **meaningfulness** of measures. These considerations include how easily the measures can be interpreted, how valid the interpretation is, and thus whether they can be used as a sound basis for assessments, comparisons, and decisions.

2.3.3 Metrics Classification per Dimension and System

As stated above, Human-Autonomy Teams can take many functional compositions, where typically one or several human operators, with one or more associate software agents, separately or jointly supervise or control one or more unmanned platforms using various degrees of automation, behaving as a team. Figure 2-2 illustrates multiple functional system levels for which metrics may be defined using Universität der Bundeswehr IFS notation [44] and their example of a work system with workers, tools, associate agents, and manned and unmanned platforms. Combinations of these entities form functional subsystems, for example a co-pilot and co-pilot's associate together instructing and supervising a group of UAVs, a software agent on each UAV performing supervision and control of the UAV, etc. Metrics in each of the categories outcome, process, and property can then be defined for each of these functional subsystems which are indicated by blue ovals in Figure 2-2. Human-Autonomy Teaming (middle; HAT1) has an environment that can consist of other HAT entities and other Human Teamings (HT), which may be grouped into functional systems.

Table 2-2 illustrates some examples of this mapping of metrics on dimensions and functional subsystems, for a hypothetical airborne surveillance task/mission environment:

- Starting with the single pilot, a number of emergent properties can be measured, including for example workload [45]. As a process measure of attention, Eye-Point-Of-Gaze (EPOG) measurements [46] may provide indications of the pilot's attention over time.
- For the two-pilot team, measurements and metrics such as communicative acts [47] (a process measure) may be defined.
- For an individual UAV with associate software agent, the number of threats detected could be an outcome measure. Note that it in this example is the functional system of the platform with sensors and

the platform-controlling software agent that perform this function jointly. Process measures such as flight efficiency metrics may thus also be defined for this subsystem.

- For the "joint cognitive system" of the cockpit [48], in this example a two-pilot airborne team with associate software agents (controlling surveillance UAVs through their respective associates), a number of attention and dialog management processes may be defined, including communication, shared processes for attention management [49], interacting with automation [50] (associates), and decision dialog between agents [51], all of which may provide process measures. Outcome measures could be the number of threats detected or managed. An emergent property for the cockpit system could be agility in rearranging the configuration of interaction between entities [52].
- If a large number of surveillance UAVs with associate agents would team-up into a swarm [53], [54], metrics on emergent properties such as coherence of concerted action and stigmergy [55] could be defined on the swarm.
- At the Human-Autonomy Team level, in this example a two-pilot airborne team with associate software agents controlling surveillance UAVs through their associates, the effectiveness of the mission as a whole could be an outcome metric, as well as a number of communicative and negotiative process metrics, and emergent system properties such as agility [52] or resilience [56], [57].
- Higher-level groupings of multiple Human-Autonomy Teams that cooperate to achieve a joint task and metrics on the task environment could be defined in a similar fashion, such as task/mission outcome, coordination processes and task environment properties such as time pressure and threat level.

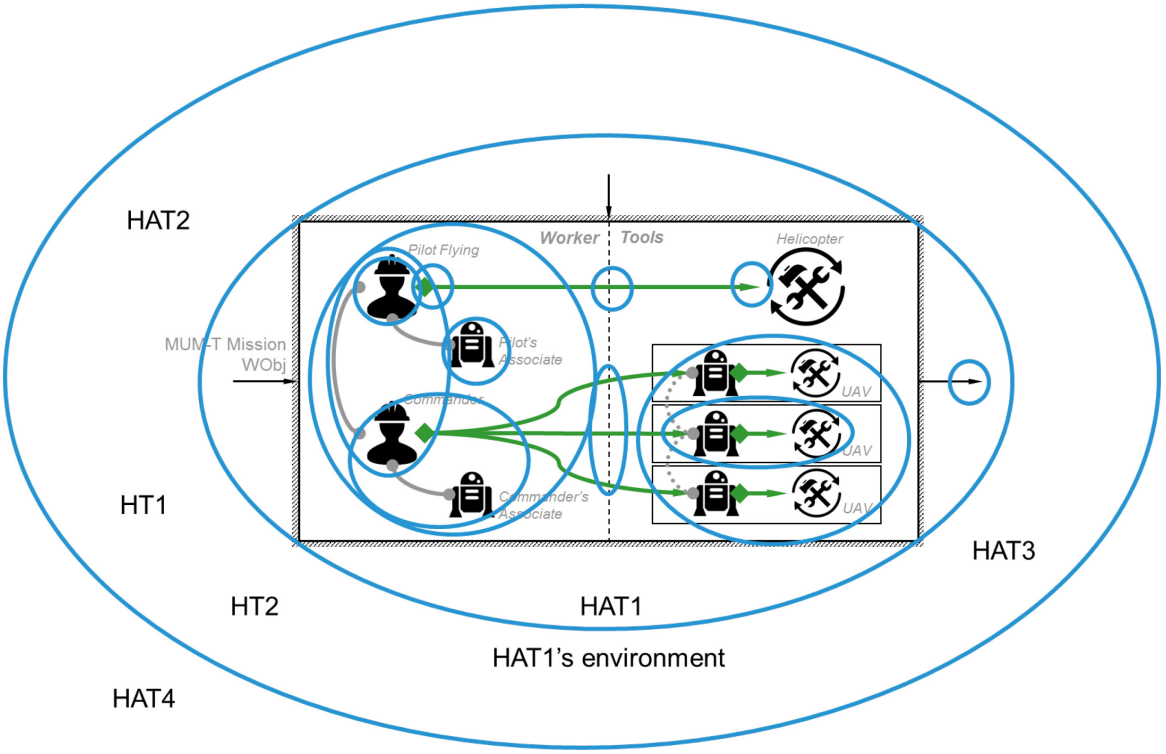

Figure 2-2: Multiple System Levels for Which HAT Metrics May Be Defined. Based on Universität der Bundeswehr IFS notation [44] and example of a work system.

Table 2-2: Examples of Subsystems and Metrics for a Hypothetical Airborne Surveillance Task/Mission Environment, for Illustration Purposes.

System for Which Metrics Are Defined	Metrics per Dimension and System (Examples for Illustration)		
	(Performance) Outcomes	Processes	(Emergent) Properties
Single pilot		Eye-Point-Of-Gaze (attention metric)	NASA TLX (workload metric)
Two-pilot airborne team		Number of pilot-pilot communicative acts of certain types (communication metric)	
Surveillance UAV with associate	Number of threats identified (mission performance metric)	Flight efficiency metrics (flight process metrics)	
Surveillance UAV swarm	Number of threats identified (mission performance metric)	Aircraft separation metrics (flight process metrics)	Stigmergy metric Coherence of action metric (coordination metrics)
HAT: Two-pilot airborne team with associate system controlling a set of surveillance UAVs	Number of threats identified (mission performance metric)	Number of HAT-negotiation (dis-) agreements, number of communicative acts of certain types, … (communications, working agreement and dialog management metrics)	Agility, resilience of HAT (metric of overall properties of whole HAT)
Context / task environment (including several HATs)	Overall mission achievement (mission performance metric)		Time pressure Mission / environment threat level

2.3.4 A Portfolio of Metrics

The purpose of the overview of dimensions and systems is to provide a way of organizing the metrics used in specific studies, such as the Technical Activities (TAs) in this working group HFM-247. The suggestions from CSE and HF team research to combine metrics in outcome, process, and property dimensions and for various system levels result in the proposal made here to compile the metrics (to be) used in a study as a portfolio of different metrics. Explicitly compiling, reflecting and iterating on this portfolio is meant to assist in determining gaps in the assessment of the various functional systems, balancing the set of metrics used to suit the purpose of study, and addressing system performance in a principled and holistic manner. This portfolio concept is based on the approach suggested for balancing safety and efficiency through reactive and proactive indicators in Ref. [58].

2.3.5 Technical Activities' Metrics Portfolios

A subset of the metrics used in the Technical Activities in HFM-247 is compiled into the following portfolio of metrics. This section compiles the metrics that the authors of the respective Technical Activities (TAs) report. For more detailed explanations of the use of these metrics within the TAs, please refer to the respective TAs described in Chapter 5 of this report.

2.3.5.1 Metrics Discussion in Connection to TA US-1 (Shively)

The following metrics per dimension and system were reported for this TA (Table 2-3).

Table 2-3: Reported Metrics per Dimension and System (Shively).

System for Which Metrics Are Defined	Metrics per Dimension and System (Examples for Illustration)		
	(Performance) Outcomes	Processes	(Emergent) Properties
Single pilot	Decision making (% correct, RT), communication confusion, error analysis (critical incident)	Eye-Point-Of-Gaze (attention metric)	NASA TLX (workload metric), trust, acceptance, usability, situation awareness

The following lessons learned were reported for this TA regarding metrics:

- What worked well? Why?
  - Our TA had a single major decision as the primary performance of the crew (where to divert). With well-trained commercial pilots, they usually made the correct choice, so we had to look more at process metrics; How did they make the decision? Did they consider all variables? How long did it take (although faster is not better in all cases)?
- What could be improved?
  - Make the decision much more difficult with some aspects that the pilots couldn't know unless they investigated.
- What metrics would you have liked to use, and/or would deserve future research?
  - Perhaps verbal protocol – that is, the pilots narrating out loud in real time what they are considering and how they are making the decision.

2.3.5.2 Metrics Discussion in Connection to TAs US-2 and US-4 (Draper, Lange)

The following metrics per dimension and system were reported for this TA (Table 2-4).

Table 2-4: Reported Metrics per Dimension and System (Draper, Lange).

System for Which Metrics Are Defined	Metrics per Dimension and System		
	(Performance) Outcomes	Processes	(Emergent) Properties
Base Defence Operations Center Operator supervising multiple heterogeneous unmanned vehicles in support of base Defence	Number of Random Anti-Terror Measures (RAMs) completed correctly Number of Normal Base Defence Events and Intruder Events responded to correctly	Process score for Normal Base Defence Events and Intruder Events: 1. Correct location; 2. Correct play; 3. Optimal vehicle; and 4. Met constraints	Situation Awareness – Accuracy and Response time to commander queries (e.g., "What is TR-22's speed?") Workload – NASA TLX

System for Which Metrics Are Defined	Metrics per Dimension and System		
	(Performance) Outcomes	Processes	(Emergent) Properties
	Number of System Failures and Environmental Events responded to correctly		
Base Defence Operations Center Operator calling plays		Time to call plays Number of mouse clicks to call plays Modality used to call plays (touch, speech, or mouse) Component used to call plays (play calling tile, radial menu, task manager)	
IMPACT System (including the operator)	Participants rated each mission task on 5-point Likert scale ranging from "Performance better with IMPACT to Performance better with Baseline"		Situation Awareness: Participants rated perceived ability of system to aid situation awareness on Likert scale (0 – No Aid to 4 – Great Aid)
IMPACT System (including the operator) (cont'd)			Perceived Value – Participants rated perceived value of system to manage UVs on Likert scale (0 – No Value to 4 – Great Value) Usability – System Usability Scale

The following lessons learned were reported for this TA regarding metrics:

- What worked well? Why?
  - One of the benefits of having a complex synthetic task environment was it brought to the fore problems that would have never arisen in a simple accuracy/response time study. Participants often got into situations, took actions, or used the autonomous system in ways that the experimenters didn't anticipate. This highlighted some potential areas of improvement for the human-autonomy team.
  - The mission scenario and operator tasks were derived from the cognitive task analysis interviews with security force personnel, and the performance outcome metrics described below were derived from what security force personnel deemed important for mission success.
- What could be improved?
  - Mission performance had to be calculated manually after the fact. It would be beneficial if the system scored operator performance in real time.

- It was difficult to tease out the value of individual autonomous components (e.g., the route planner, the intelligent agent, etc.). If this study were to be replicated, it could benefit from a few additional levels of each independent variable (i.e., gradually adding in automation capabilities and having four scenarios of gradually increasing complexity).
- Metrics may have been affected by non-expert participants. Future research would benefit from having extensively trained participants.

- What metrics would you have liked to use, and/or would deserve future research?
  - Human-Autonomy Communication.
  - Human-Autonomy Trust.
  - Number of Courses of Action examined.

2.3.5.3 Metrics Discussion in Connection to TA US-3 (Chen, Barnes)

The following metrics per dimension and system were reported for this TA (Table 2-5).

Table 2-5: Reported Metrics per Dimension and System (Chen, Barnes).

System for Which Metrics Are Defined	Metrics per Dimension and System		
	(Performance) Outcomes	Processes	(Emergent) Properties
Human Mission Commander (MC)	MC's situation awareness of the mission environments involving intelligent agents (unmanned vehicles and software agents)	MC's awareness and understanding of the agents' current actions and plans, reasoning process, projected outcomes and uncertainty	Operator's situation awareness (situation awareness probes) Operator's perceived workload (NASA TLX) Operator's attention (eye movement metric)

The following lessons learned were reported for this TA regarding metrics:

- What worked well? Why?
  - Assessment of operator's calibration of his/her trust in the agent using the Signal Detection paradigm (choosing between agent's recommended plan vs. a back-up plan with ongoing developments in the environment); this metric captures human-agent teaming effectiveness.
- What could be improved?
  - Subjective trust measures (not always consistent with behavioral trust data).
- What metrics would you have liked to use, and/or would deserve future research?
  - Real-time assessment of subjective trust.

2.3.5.4 Metrics Discussion in Connection to TA GER-1 (Schulte, Donath)

The following metrics per dimension and system were reported for this TA (Table 2-6).

Table 2-6: Reported Metrics per Dimension and System (Schulte, Donath).

System for Which Metrics Are Defined	Metrics per Dimension and System		
	(Performance) Outcomes	Processes	(Emergent) Properties
Reconnaissance UAV with cognitive agent on board	Number of identified detected objects/threats (mission performance) Reconnoitered area Air space / no fly zone violations		Modified Cooper Harper Rating (Acceptance/Usability)
Team of reconnaissance UAVs, each of them with cognitive agent on board	Number of identified detected objects/threats (mission performance) Reconnoitered area Air space / no fly zone violations		Modified Cooper Harper Rating (Acceptance/Usability)
Commander with team of UAVs and on-board agents	Number of correct identified objects Number and type of task assignments to UAVs Interaction Effort Neglect Tolerance Number of accepted/modified/rejected UAV planning proposals Reaction time w.r.t. to UAV proposals	Eye Movement (attention allocation) Manual Interactions	NASA TLX (workload w.r.t. UAV tasking/handling) Attention Demand Situation Awareness
HC Pilot with associate system	Complexity of planning proposals Type/Time/Situation of new planning proposals Reaction times w.r.t. plan proposals Number and kind of proposed plan modifications Number and kind of interventions/support by the associate system	Eye Movement (attention allocation) Manual interaction behavior Communication (internal/external) Task activity and mental state	NASA TLX (workload w.r.t. mission plan complexity) Plan awareness Trust Usability

System for Which Metrics Are Defined	Metrics per Dimension and System		
	(Performance) Outcomes	Processes	(Emergent) Properties
Commander with associate system	Number of warnings/hints/ support of the assistant system w.r.t. the commander's tasks Frequency of the use (w.r.t. time/situation) of the different level of automation for UAV tasking Number and kind of interventions/support by the associate system	Eye Movement (attention allocation) Manual interaction behavior Communication (internal/external) Task activity and mental state	NASA TLX (workload w.r.t. UAV tasking/handling) Usability
HC Pilot and Commander with multiple UAVs and on-board cognitive agents for the UAVs	Flight time over not reconnoitered area	Eye Movement (attention allocation) Manual interaction behavior Communication (internal/external) Task activity and mental state	NASA TLX (workload w.r.t. mission complexity)
Context / task environment (including several HATs)	Mission achievement (mission performance) Required time for mission accomplishment (in time critical missions) Flying time and distance over potential threatened / (not reconnoitered) area		Time pressure Mission / environmental threat level

The following lessons learned were reported for this TA regarding metrics:

- What worked well? Why?
  - Very realistic mission scenarios and simulator environment leads to an immersion of the operators within the virtual environment. The scenarios were gathered during extensive knowledge acquisition interviews with mission-experienced military helicopter pilots in the run-up to the experiments.
  - Human-in-the loop experiment within a complex MUM-T simulation environment with holistic data acquisition. These allow the analysis of human-autonomy teaming aspects from different points of view.
  - Online activity and mental state determination of the helicopter crew as trigger for adaptive support of the associate system (closed-loop functionality).
- What could be improved?
  - Future training should be more adaptive to the individual needs of operators to have a uniform qualification level at the end of the training.

- It was difficult to address all individual (subsystem) aspects/measures within the overall mission experiment.
- More subjects would be required for quantitative/statistical analysis.

- What metrics would you have liked to use, and/or would deserve future research?
  - Real-time assessment of additional psychophysiological data for individual, objective, real-time workload assessment.
  - Human-Human / Automation-Automation / Human-Automation / Autonomy effectiveness.
  - Online situation awareness assessment.

2.3.5.5 Metrics Discussion in Connection to TA GER-2 (Baltzer, Flemisch)

The following metrics per dimension and system were reported for this TA (Table 2-7).

Table 2-7: Reported Metrics per Dimension and System (Baltzer, Flemisch).

System for Which Metrics Are Defined	Metrics per Dimension and System		
	(Performance) Outcomes	Processes	(Emergent) Properties
Trajectory adaptation by driver and automation	Lateral Displacement in lane in allowed area Current velocity (not higher than allowed speed limit) Safe headway to car in front (Time to Collision, TTC)	Steering, and gas and brake pedal use (Driver can adapt lateral displacement by steering between lane markings. Driver can adapt speed using gas and brake pedal between 0 and speed limit. Driver can adapt speed using gas and brake pedal when following another car between 0.5 to unlimited seconds TTC)	Driver situation awareness (how much space to left or right side), collisions, workload
Mode transition by driver and automation	Driver understanding of driving responsibilities Take over time Driving performance (lateral displacement from lane center after transition) Transition quality	Report of current driving responsibilities (Think aloud technique: I need to control, automation has no tasks vs. I need to supervise driving control and can initiate maneuvers and automation performs driving control tasks vs. I have no driving tasks, automation has all driving tasks) Time measurement between Automation mode transition initiation and confirmation by driver Steering, and gas and brake pedal use Participant rating of transition	Driver mode awareness, mode confusion, efficiency, controllability, safety, usability and acceptability
Maneuver change by driver and automation	Understanding of current maneuver	Report of time and space implications of current maneuver (think aloud technique)	Situation Awareness and Traceability: driver knowing what the automation is trying to do

The following lessons learned were reported for this TA regarding metrics:

- What worked well? Why?
  - Driver understanding of current situation could be gathered well using the think aloud technique, because they could include respective reasoning.
  - Combination of measuring and reporting was good, because it gives more explanation why certain behavior/action/performance could be observed.
- What could be improved?
  - A more structured Q&A while driving would give a more complete picture of the driver's understanding of the current situation.
- What metrics would you have liked to use, and/or would deserve future research?
  - Joy of use.
  - User Experience.
  - Trust.

2.3.5.6 Metrics Discussion in Connection to TA FRA (Coppin)

The following metrics per dimension and system were reported for this TA (Table 2-8).

Table 2-8: Reported Metrics per Dimension and System (Coppin).

System for Which Metrics Are Defined	Metrics per Dimension and System		
	(Performance) Outcomes	Processes	(Emergent) Properties
Single pilot	Communication quality, communication confusion, loss or maintain of common ground	Correlation of physiological measurement and human-human communication protocols	Communication accuracy Workload and stress

The following lessons learned were reported for this TA regarding metrics:

- What worked well? Why?
  - It was demonstrated that physiological measurement was technically accessible in a realistic environment (RAFALE training simulator) and valuable for the understanding of Operator Functional States by the training session leader.
  - The experiment relied on the preliminary analysis and formal definition of mission context, cognitive and task models, which filled a gap in the understanding of cooperative tasking within a fighter patrol, in human-human configurations and in future potential human-autonomy ones.
  - The extraction and classification of operator functional states comforts the perspective of an adaptation loop within the human-autonomy system, especially at communication level.

- What could be improved?
  - The use of the communication facilitator (called conductor in the project) has still to be better defined and evaluated in terms of improvement of performance, as the first experiment only focused on the feasibility aspects.
  - The classification parameters (and optimal) performance should rely on long-term measurement and larger sets of data to be more robust.
  - The analysis of team behavior would need to register and process simultaneously several pilots and not only one to better study the effect and impact of miscommunicating.
- What metrics would you have liked to use, and/or would deserve future research?
  - Human-Autonomy Communication.
  - Human-Autonomy Trust.

2.3.5.7 Metrics Discussion in Connection to TA NL (Neerincx, van Breda)

The following metrics per dimension and system were reported for this TA (Table 2-9).

Table 2-9: Reported Metrics per Dimension and System (Neerincx, van Breda).

System for Which Metrics Are Defined	Metrics per Dimension and System		
	(Performance) Outcomes	Processes	(Emergent) Properties
Ontology-based situation awareness module for (adaptive) shared control	Accuracy and completeness of objects' identification. Size of the area explored	Duration (time from start to completion of (sub-)task) and mental effort	Situation Awareness (SAGAT). Cognitive and affective load
Adaptive work agreements module for information sharing, coordination and task allocation	Accuracy and completeness of joint activities and the contributing information sharing	Task (re-)allocation and efficiency of resource deployment	Trust (questionnaire). Workload distribution
Explainable AI module for the construction of deliberative, contrastive and example-based explanations	Number and percentage of achievements concerning (joint) operational and/or learning goals	Behaviors' compliance with norms, advices and recommendations	Trust (questionnaire). Motivation (as shown in attention, effort, emotion and questionnaire)

The following lessons learned were reported for this TA regarding metrics:

- What worked well? Why?
  - Overall, the "classical" metrics to assess team members' individual performances worked well, as well as the Cognitive and Affective Load measures to assess workload harmonization. A rich foundation of empirical human factors research helped to acquire these results.

- What could be improved?
  - The measurements of individual (team members') performances over time (longitudinal).
  - The objective measurement of trust.
- What metrics would you have liked to use, and/or would deserve future research?
  - Team coherence.
  - Team resilience.
  - Trust development over time.

2.3.5.8 Metrics Discussion in Connection to TA UK (Lashley, Taylor)

The following metrics per dimension and system were reported for this TA (military applications where metrics were tested: MUM-T, MUxV, C2, Base Protection, ISR PED, Strike, Overwatch, CASEVAC, VBIED, TIC) (Table 2-10).

Table 2-10: Reported Metrics per Dimension and System (Lashley, Taylor).

System for Which Metrics Are Defined	Metrics per Dimension and Subsystem		
	(Performance) Outcomes	Processes	(Emergent) Properties
System Operator (self-assessed)	Taskwork Performance, Decision Quality, Probability of Mission Success	Collaboration, Adaptability Proficiency, Influence Power	Workload, Situational Awareness
System Operator (observed)	Team Workload, Team Performance, Team Decision Making, Probability of Mission Success	Communication, Support, Collaboration, Adaptability Proficiency	Shared Situational Awareness, Leadership
Autonomy system			Trustworthiness (Reliability, Dependability, Predictability, Resilience, Safety, Security and Availability)
Operator and system teaming		Risks (Mission Critical Decision Teaming Event, Description, Probability, Severity, Mitigation) Capability Maturity Tool Usability (observed) and Tool Utility (observed and self-assessed)	REMEDE (Recognize, Evaluate, Mitigate, Execute, Dialog, Effects)

2.3.6 Metrics Portfolio Discussion and Future Research

To conclude, the metric portfolios reported in the separate Technical Activities demonstrate a large variety in the functional subsystems that they addressed. However, all TAs report that they employ a portfolio of combined outcome, process, and properties of the functional systems that make up human-autonomy teams. Relatively traditional human factors metrics are combined with more innovative metrics that focus on teaming aspects. Improvement potential for the portfolio of metrics of the TAs have been discussed. The use of metrics is however specific to the Technical Activities that focus on quite different tasks and functional systems, which makes the metrics difficult to compile and compare in a single comprehensive list, considering the risk of interpreting the use of the metrics out of their experimental context. This applies also to the reported lessons learned on what worked well and what could be improved in the TA metrics portfolios.

However, the following list, ordered from teaming to individual operator metrics, may provide an indication of some of the ambitions and suggestions of HFM-247 participants' future use and employment of metrics in human-autonomy teaming studies:

- Human-Autonomy Trust (mentioned 5 times, incl. once "in real time", once "over time");
- Human-Autonomy Communication. (mentioned 2 times);
- Human-Human / Automation-Automation / Human-Automation / Autonomy effectiveness;
- Team coherence;
- Team resilience;
- Number of Courses of Action examined;
- Real-time assessment of additional psychophysiological data for individual, objective, real-time workload assessment;
- Online situation awareness assessment;
- Verbal protocol; and
- Joy of use, user experience.

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Chapter 3 – MILITARY RELEVANCE

Helen Keirl and Robert Taylor
DSTL
UNITED KINGDOM

Antony Grabham
DSTL
UNITED KINGDOM

Mike Thomas
QinetiQ
UNITED KINGDOM

3.1 OVERVIEW AND SCOPE

This section describes the broad concepts and doctrine guiding the exploitation and military use of autonomy, and more specifically, Human-Autonomy Teaming (HAT). Technological limitations, legal and moral constraints, and most effective human involvement suggest that some form of human-in-the-loop control always will be required. This means finding the right balance of human supervision and automation must be identified in context. In order to determine the level of supervision required to complete a mission use cases can be used to test automation concepts in realistic scenarios. This section describes an endorsed scenario and three militarily relevant use cases, providing a representative, routine and stressing, military context of use for HAT concepts and technologies. The intention is to show where and how, by presenting specific examples of use, each national Technical Activities (TA) or HAT design pattern can be applied and exploited for military benefit, with the ability to consider the strengths, weaknesses, opportunities and risks of HAT.

3.2 INTRODUCTION

> *The use of drones, or unmanned aerial vehicles, has increased exponentially in the last 10 years, and this trend is likely to continue for the foreseeable future.* [1]

Remote and automated systems employing unmanned and remotely operated platforms, and systems with embedded automation and self-governing autonomous functionality, are being increasingly employed as enablers of military capability. Ultimately, advances in automation, autonomy and human-autonomy teaming are a means to end, namely, in a military context, to improve the probability of mission success. They are widely used by military commanders to act as force-multipliers and augmenters of the force, and adding a valued component to the military force mix. Unmanned Vehicle (UxV) technologies are considered to have proven their value to air and ground military operations even with limited autonomous capabilities and relatively immature concepts of operation [2]. Catalogues of utility and use, with classifications of unmanned and remotely operated platforms and robotics abound. They identify the extensive breadth and depth of applications of increasingly advanced automation technologies employed in military systems across a myriad of applications, functions, missions and tasks. The military relevance of advanced automation technologies is thus, ever more self-evident. However, what such catalogues frequently lack is an appreciation and accounting of the human resources capabilities and often extensive manpower footprint needed to field and operate these "unmanned" systems. In particular, they lack definition and discrimination of nature and demands of the human roles in the command and control of highly automated military systems.

Developments in automated and self-governing autonomous technologies, together with understanding of technological limitations, and legal and moral constraints on the use of weapon systems, have focused attention

on the need to maintain the most effective human involvement in unmanned systems [3]. The necessity of human involvement in control of weapon systems means that it is fundamental and axiomatic that there is a human in charge [4]. Human effectiveness remains the key to all military capability. Unmanned platforms are needed to be operated under human control, with human oversight and supervision providing human judgement of risk in uncertainty, and with automation and self-governing autonomy acting as tools for human use. Rather than seeking autonomous systems that operate independently of human control, so as to cope with the risks of unreliable human supervisory control (vigilance deficit, inattention/distraction, cognitive bias, performance variability/error), or simply removing the operator from the control loop entirely, autonomy is needed that operates actively in support of the human in human-computer or machine partnership teaming, forming a synergistic and symbiotic relationship, as implemented in advanced pilot assistance systems [5].The stretch challenge goal for autonomy needs to be enhancing HAT and cognitive cooperation [6], in an adaptive human-computer decision partnership, exemplified by enabling an advanced human-centric capability for multi-aircraft control [7] and Manned-Unmanned Teaming [8]. In summary, self-governing autonomy is needed not to provide solely technology-centric solutions, but a socio-cognitive systems approach [9] which actively and purposefully seeks to enhance human cognition and understanding, improving human competency, authority, responsibility and accountability, and that ultimately serves directly the betterment of human purposes, judgement and values (cf. Asimov's Laws of Robotics).

In 2004, NATO Industrial Advisory Group 75 advised on the advantages of UAVs [4], believed to include the following:

- Reduced risk to humans;
- Optimising human performance;
- Reduced training requirements;
- Improved contingency management;
- Reduced data link demands; and
- Increased operational flexibility.

Currently, and in contrast, automated functions for unmanned and remotely piloted aircraft, such as for take-off and landing, height, speed or station keeping, and automatic sensor operation, are commonly regarded as being designed in relation to a similar simple set of objectives [3]:

- Reduce operator workload;
- Increase reliability;
- Increase capacity to control or monitor the most important elements of the mission; and
- Speed up decision making.

It is widely recognised that there are substantial operational benefits and potential perils associated with the use of autonomy. The strengths and challenges of UAVs were identified concisely and usefully by Air Chief Marshall Burridge as follows [10]:

Strengths:

- Dealing well with 3D tasks – dull, dirty and dangerous;
- Potential response at a number of levels, ranging from resolving tactical firepower problems to providing commander's strategic critical information requirements;

- Ease of retasking;
- Increase stand-off ranges for kinetic, and non-kinetic or cognitive attack; and
- Persistence.

Challenges:

- Interoperability of systems;
- Vulnerability;
- Limited capacity to address a wide surveillance;
- Insatiable demand for bandwidth; and
- Inability to deal with ambiguity in the same way as manned aircraft.

More broadly, if applied correctly, such as principally through HAT, autonomy can serve to increase decision speed and agility, and in so doing, help military commanders and operators to sustain military advantage [11].

Through-life capability management identifies common lines of facilities that support and service military platforms through their life, termed the 'Defence Lines of Development' (DLoD) needed together to deliver military capability to operational users, namely:

- Training;
- Equipment;
- Personnel;
- Infrastructure;
- Doctrine and concepts;
- Organisation;
- Information;
- Logistics; and
- Interoperability[1].

In simple terms, these DLoDs represent where technologies from the research and development space, such as autonomy, enter into the product space. They are a necessary consideration in relation to the military utility and exploitation of autonomy concepts. Other NATO nations have equivalent common defence facilities [12].

Focusing on doctrine and concepts, previous analysis giving consideration of impact on human roles of automation in military operations has referenced the UK MoD Defence Capability Framework (DCF) as useful initial broad conceptual context for analysis of military relevance [13]. UK DCF is illustrated in Figure 3-1. Currently, the UK Joint High-Level Operational Concept (HLOC) focuses at the strategic and operational level by using the UK DCF [14]. DCF distinguishes seven components of high-level capability, organised on three axes, namely Command and Inform, Sustain and Protect, and Prepare, Project, and Operate.

[1] The Defence Lines of Development (DLoDs) are UK MoD's classification of the constituents of defence capability, and part of the MoD's Architecture Framework (MoDAF). Although not a DLoD in itself, interoperability is considered an intrinsic part of the framework.

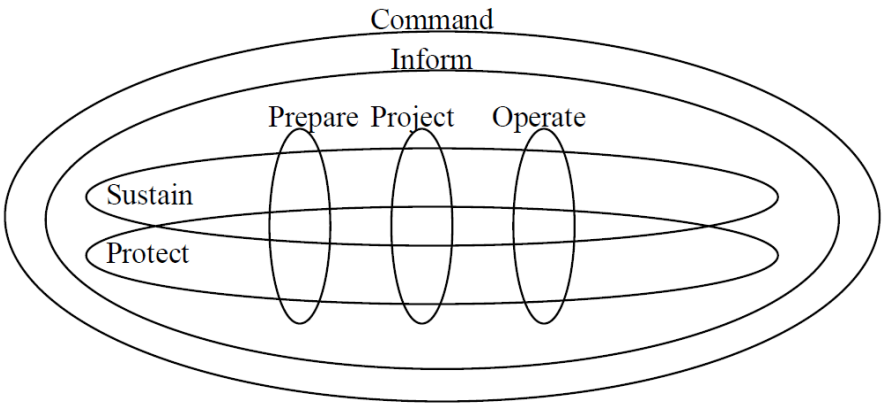

Figure 3-1: Defence Capability Framework.

Prioritisation in current operating doctrine of Effects-Based Operations (EBO) has focused HLOC analysis on the Operate core capability concept, which is defined as follows:

> *An agile, task-oriented joint force with freedom of action to synchronise effects throughout the Battlespace and with maximum potential to exploit fleeting opportunities.*

Agility is identified as having both physical and mental dimensions, but it is regarded as an essentially a human-centric attribute involving creativity, resourcefulness and imagination enabling adaptation with versatility, to the unexpected. This reflects the adoption of a manoeuvrist approach, providing freedom to manoeuvre with decision and force agility. Understanding of agility identifies the following attributes:

- Responsiveness – Speed in the recognition of the need for action or change, and to seize the initiative;
- Robustness – The degree to which a force is effective across a wide range of situations and missions;
- Flexibility – The capability to identify and execute actions along multiple paths to success; and
- Adaptability – The degree to which a force learns rapidly about new operating environments and acts upon that knowledge.

Adaptability is considered to increases in importance when operating in unfamiliar situations. Military understanding considers that adaptability should be measured in three ways:

- The development of the decision-maker's critical information requirements. This needs to be accurately defined, and then the correct balance needs to be formed between information gathering and the optimum tempo of decision making;
- Identification of anomalies as predicted patterns fail to unfold; and
- Acting effectively in novel situations.

Work on adaptability proficiency performed under the UK MoD Autonomy Research Programme, reported here under the UK HAT Collaborative Validation and Verification (CV&V) TA, has identified a range of military relevant, adaptive capacity variables applicable to Test and Evaluation (T&E) of autonomy technologies, including constraints, enablers, resources, altered situations, decisions and adjustment strategies, The adaptive capacity variables identified are illustrated in Figure 3-2.

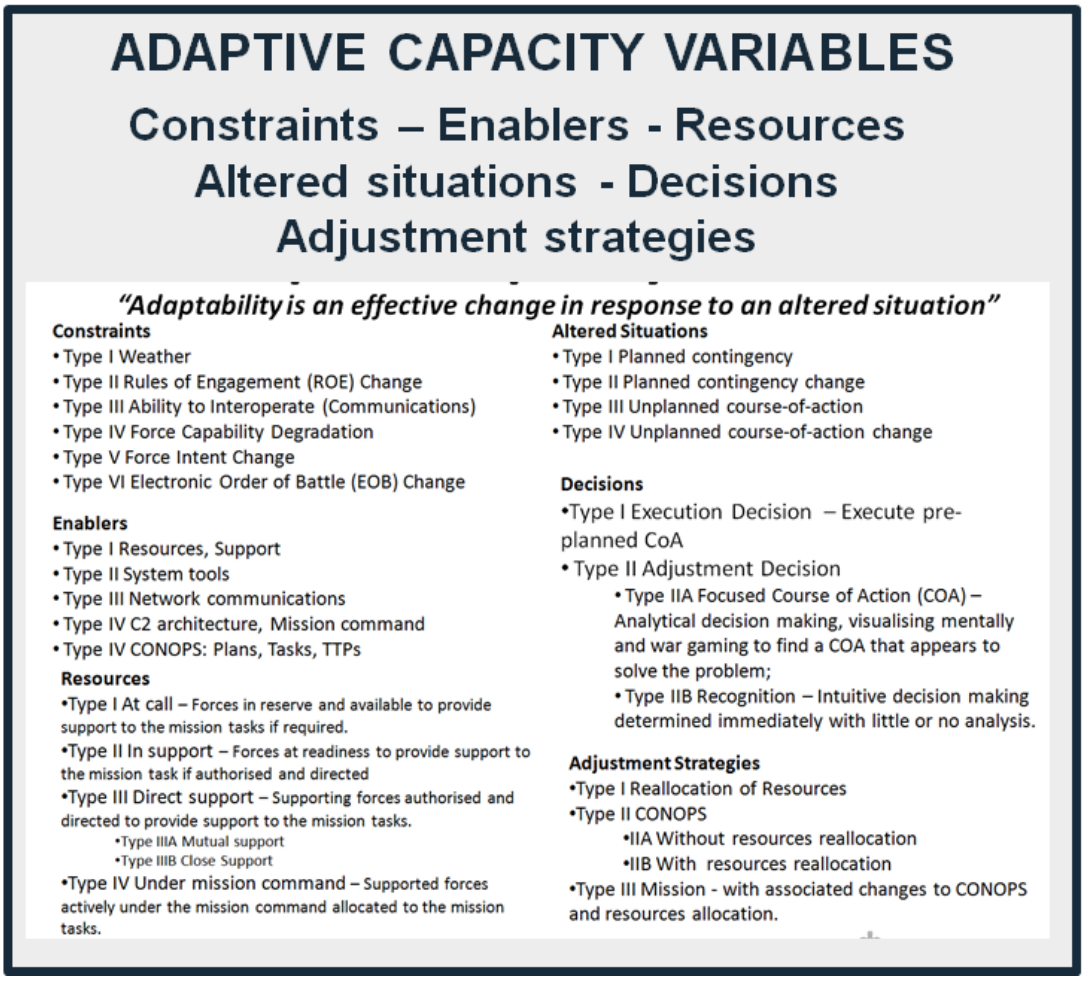

Figure 3-2: UK MoD Autonomy Research Programme Adaptive Capacity Variables for Autonomy CV&V.

The ability to develop and sustain an enduring and agile Command and Control (C2), exploiting information, being more integrated as a force, and being more adaptable to changing circumstances, are at the heart of the UK MoD Future Force Concept. Agile C2 is seen as requiring a socio-technical system, involving changes to people, processes, structures and technology, to be fit for the information age and to exploit the cognitive advantages of both human and machine [15].

Elsewhere, including the US, the need for agility in military operations is widely recognised and prioritised. In Air Force Future Operating Concept (AFFOC) 2015 [16] the following vision for operational agility is described:

> *In 2035, AF forces will leverage operational agility as a way to adapt swiftly to any situation or enemy action. Operational agility is the ability to rapidly generate – and shift among – multiple solutions for a given challenge. By using operational agility as a guiding principle in the conduct of our core missions, we can preserve the Air Force's ability to act quickly in response to any challenge.*

3.3 IDENTIFICATION OF MILITARY RELEVANCE THROUGH SCENARIOS AND USE CASES

In 2012, the US DoD Defense Science Board Task Force on The Role of Autonomy in DoD Systems [2], provided recommendations focused on overcoming the operational difficulties preventing exploitation of the full potential of autonomous systems. Concerned about the technology-centric focus in DoD research, on for example, identification of Levels of Autonomy, they identified a guiding reference framework, illustrated in Figure 3-3, to address the military needs of autonomy design, with three facets, namely cognitive echelon (e.g., Command and Control Levels), mission timelines, and human-machine system trade spaces, with particular reference to adaptive capacity. This was to provide explicit focus in autonomy design on the following:

- Design decisions on the explicit allocation of cognitive functions and responsibilities between the human and computer to achieve specific capabilities;
- Recognition that these allocations may vary by mission phase as well as cognitive echelon; and
- Making the high-level system trades inherent in the design of autonomous capabilities visible.

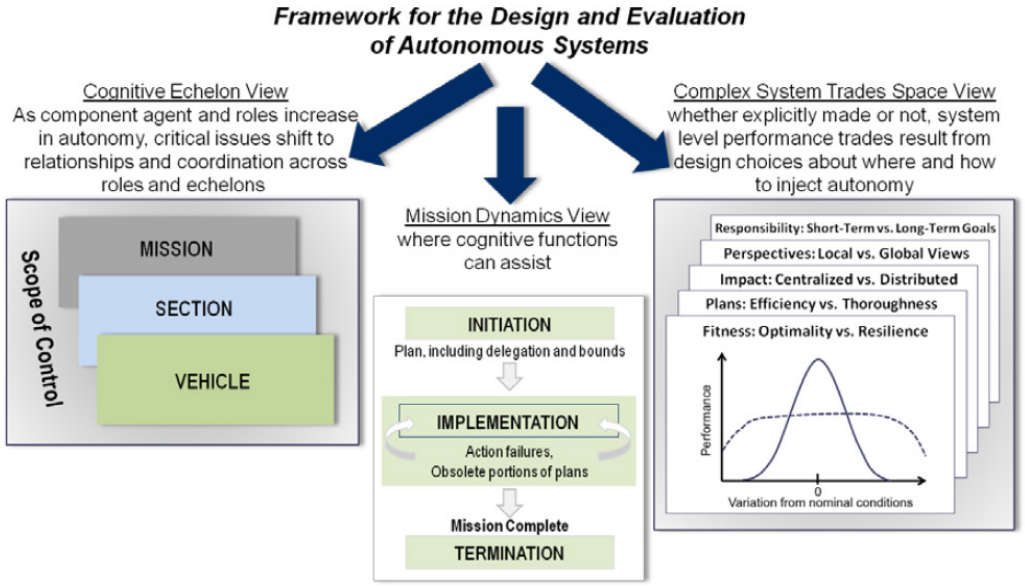

Figure 3-3: DoD DSB Framework for the Design and Evaluation of Autonomous Systems.

Representative and stressing Military scenarios and use cases for autonomy and HAT enable the analysis of human-machine system trade spaces with reference layers of C2 and mission timelines and objectives.

Military scenarios and use cases can provide a military relevant context and reference basis for considering human factors issues associated with the exploitation of automation and autonomy concepts and technologies. Scenarios are ways of characterising future military threats and challenges. They are tools for operational analysis that provide a means for evaluating capabilities and capability gaps, investigating military effectiveness and estimating cost/benefits for investment purposes. Additionally, as intended here, scenarios are useful tools for system engineering, providing the basis for mission analyses, including representative tasks, targets, threats and tactics. They are used to develop understanding of system functions, processes and

information requirements, and for exploring, developing and validating applicable Tactics, Techniques and Procedures (TTPs). Use cases are relatively short "snapshots" or "vignettes", comprising focused episodes or events of use, extracted from scenarios. They are used systems engineering for testing the utility of system and tool prototypes, presented for visualisation in a "cognitive walkthrough", or simulated in synthetic or live dynamic environments. They can provide a meaningful evaluation of their usability and effectiveness, performed under typical or stressing conditions with exposure to a range of envisioned operating conditions and variables. The selection criteria for scenarios and uses cases are important. Selectivity involves the inherent risks of being unrepresentative. It risks biasing analysis, introducing irrelevant or limiting focus, and setting overly restrictive boundaries and limitations to thinking. Notwithstanding, verifiably representative use cases, obtained from credible and knowledgeable sources, such as military advisors and subject matter experts, can provide an efficient and effective means of communicating understanding of requirements and for sharing appreciation on likely and probable performance in contexts of use. This is particularly valuable for considering the use of new concepts and technologies.

NATO SAS-16 used a Peace Support Operations scenario with UAV capabilities in Composite Air Operations (COMAO) to derive conclusions on Unmanned Air Vehicle (UAV) integration. HFM-018 work to identify human-centric requirements required more detailed task specificity for a Composite Unmanned Military Vehicle (UMV) scenario [5]. For example, 17 UAV tasks were identified as required to complete an airfield attack in Article 5 operations comprising Ingress (5), Over Target (8) and Egress (4) elements. A Composite UMV scenario was developed by HFM-078 to illustrate the possible functioning of UMVs. This UMV scenario was decomposed into multiple phases (Period of Increased Tension; Transition to War; Conflict), multiple domains (Space, Air, Sea and Land) and multiple Unmanned Ground Vehicle (UGV), Unmanned Underwater Vehicle (UUV) and UAV task elements. A total of 25 discrete tasks were identified, across the three scenario phases and four domains, comprising Space (5), Air (5), Sea (7) and Land (8) linked task components. The analysis was represented graphically with connecting task links to indicate the order and flow of the contributing components.

For the purposes of HFM-247, at the 2nd TG Meeting at CMRE, 10 November 2014, a set of four common scenarios was proposed by UK for consideration of HAT requirements. These were taken from the work of NATO Industrial Advisory Study Group (NIAG SG-157), on Multi-Domain Unmanned Vehicle Control. They were developed by NIAG to support requirements development for a NATO Multi-Domain Control Station (MDCS). This was to be done through the development of system architecture, an application domain model and Information Exchange Requirements (IERs). The MDCS scenarios and operational use cases comprised the following elements, supported by detailed use case descriptions, with a listing of mission activities and key elements:

- Maritime Surveillance and Interdiction;
- Convoy Protection from IED;
- Airfield / High-Value Asset Security; and
- Harbour Protection.

An illustration of the possible mapping of HFM-247 TAs to these four MDCS scenarios was proposed (Figure 3-4), constructed on the basis of the information available at the 2014 2nd TG HFM-247 Meeting. This indicated potentially good mapping to a Base Protection scenario with a Convoy Improvised Explosive Device (IED) component.

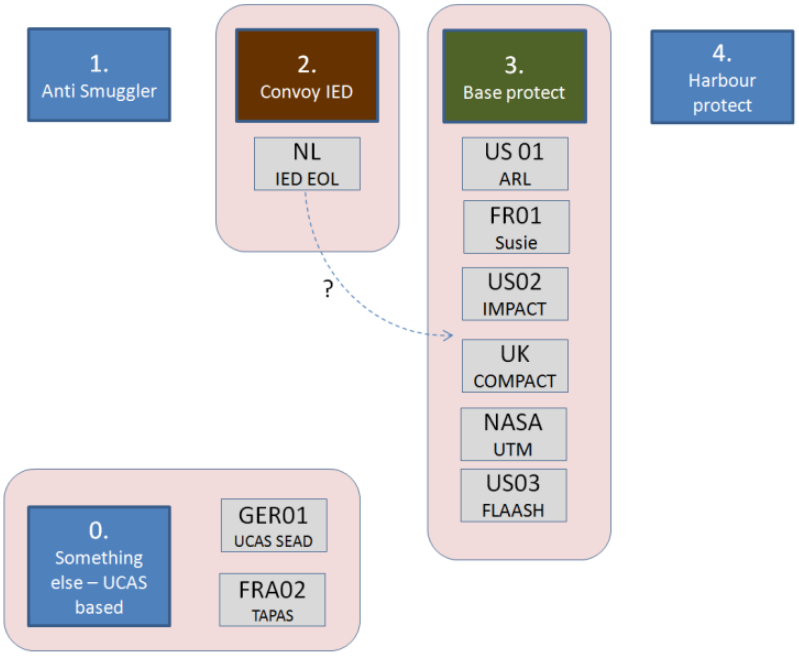

Figure 3-4: Mapping of 2014 HFM TA Activities to MDCS Scenario Use Cases.

3.3.1 Background Scenario

For wider context to the use cases the following is the background scenario from Joint Warrior. Joint Warrior is a UK tri-service multinational exercise that involves numerous warships, aircraft, marines and troops. It provides a complex environment and a range of scenarios in which NATO and allied units can go through training together in tactics and skills for use in a combined joint task force [17].

This background scenario was chosen because it is across three domains and features realistic challenges and complexities for NATO allies.

Dragonia is undergoing rapid destabilisation and fragmentation due to Ethnic Saxonian insurgency led by the Free Saxonian Brotherhood (FSB). The country has lost effective control of parts of the Northern Disputed Zone (NDZ) which is rapidly becoming an ungovernable space (Figure 3-5).

Saxonia is adopting aggressive rhetoric against Dragonia and calling for Ethnic Saxonian recognition. Saxonia has aggressively increased its activity and posture along the border with Dragonia and raised the readiness and number of its armed units.

Saxonia has mobilised a number of brigades to the border region and is conducting “readiness and reaction drills” in the area, ostensibly to conduct refugee support and peace enforcement operations.

Tensions in the region are critical with the risk of miscalculation and rapid escalation a very real possibility. Reporting indicates that in the event of hostilities Saxonia would look to use its extensive fleet of Fast Inshore Attack Craft (FIAC) and Fast Attack Craft (FAC) and Submarines to neutralise international maritime forces before committing forces to a ground offensive.

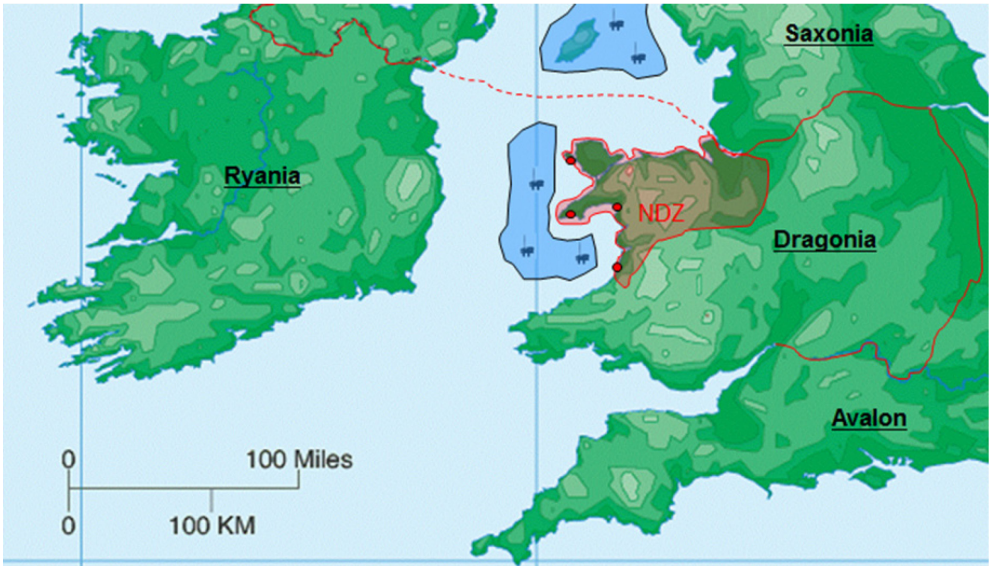

Figure 3-5: Mapping of Joint Warrior Scenario.

3.3.2 Theatre Scenario

In order to pursue stabilisation in the area, and as a show of support the Government of Dragonia (GoD), International Coalition forces have secured a Forward Operating Base (FOB).

The unrest within the Dragonian population has led to a number of large crowds gathering around the FOB perimeter, and concerns exist within the coalition that the terrorist activity seen in major conurbations may lead to an attack on civilians in this area. FSB operatives have been observed conducting recce of FOB defences.

Saxionian FAC have been observed making arms drops along the Dragonian coast. In addition to this activity, these vessels have been increasingly harassing civil vessels entering and exiting the port area, and appear to be conducting reconnaissance of the Coalition defences at the FOB.

The aims of the international coalition are:

- Provide demonstrable support to the GoD;
- Ensure continued security of and access to critical Dragonian infrastructure;
- Maintain continued access to sea lanes for commercial shipping; and
- Act as a peacekeeping and stabilisation force.

The aims of the Saxonia and Free Saxonian Brotherhood are:

- Further destabilisation of the GoD by undermining the stabilisation efforts of the international community;
- Encouragement of civil unrest and fragmentation within the NDZ through both non-violent and violent activity; and
- Harassment of surface vessels coming into and out of the Port.

3.3.3 Use Case One

Friendly Forces include:

- Helicopter Maritime Attack (HMA);
- Three Tactical Unmanned Air Systems (TUAS);
- One Small UAS;
- One Fast Air;
- One Support Helicopter; and
- One Operational UAS (OUAS).

Enemy Forces include:

- One Surface vessel;
- Several arms caches; and
- One land vehicle.

Human Intelligence (HUMINT) indicates potential enemy attack on the Forward Operating Base (FOB). Intelligence suggests that enemy forces will come from the sea and launch an attack on the FOB. FOB alert state rises to reflect HUMINT, requiring assets to undertake ISR collect in and around the base.

This Use Case, illustrated in Figure 3-6, focuses on the collection and dissemination of ISR in and around the FOB before adapting and rescheduling assets to changing circumstances as events unfold.

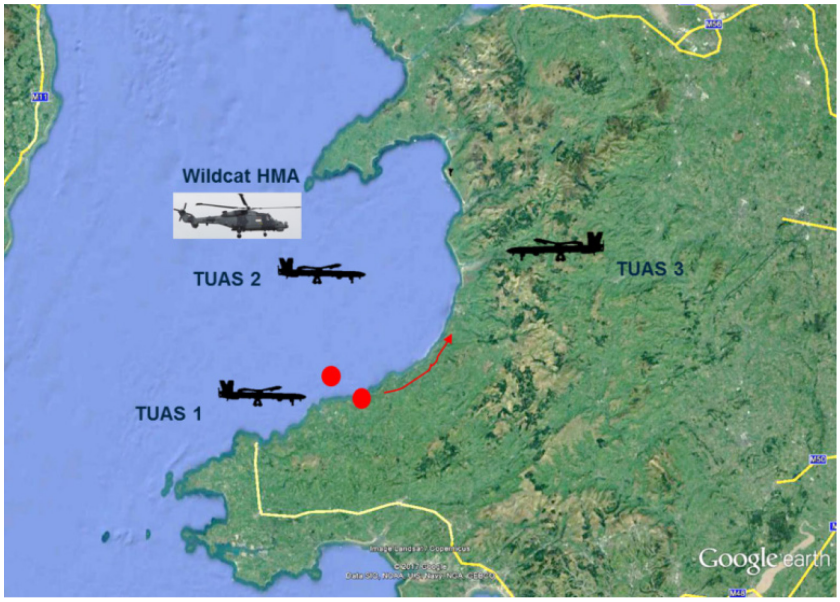

Figure 3-6: Use Case One Map.

TUAS will be undertaking a variety of ISR collect roles:

- COMINT detection (TUAS 1 – following planned ASX trial route and COMINT detections);
- Maritime Search (TUAS 2 in conjunction with HMA); and
- SAR collection (TUAS 3 – applying correct tactics profile).

SUAS will undertake localised surveillance and search within the base area including:

- Search of linear features (Fence lines);
- Point features ('Stop Gates' and Patrol Routes); and
- Area features (areas outside fence line).

3.3.4 Use Case Two

Use Case Two is illustrated in Figure 3-7. Friendly Forces include:

- Helicopter Maritime Attack (HMA);
- Three Tactical Unmanned Air Systems (TUAS);
- One Small UAS;
- One Fast Air;
- One Support Helicopter;
- Foot Patrol; and
- One Operational UAS (OUAS).

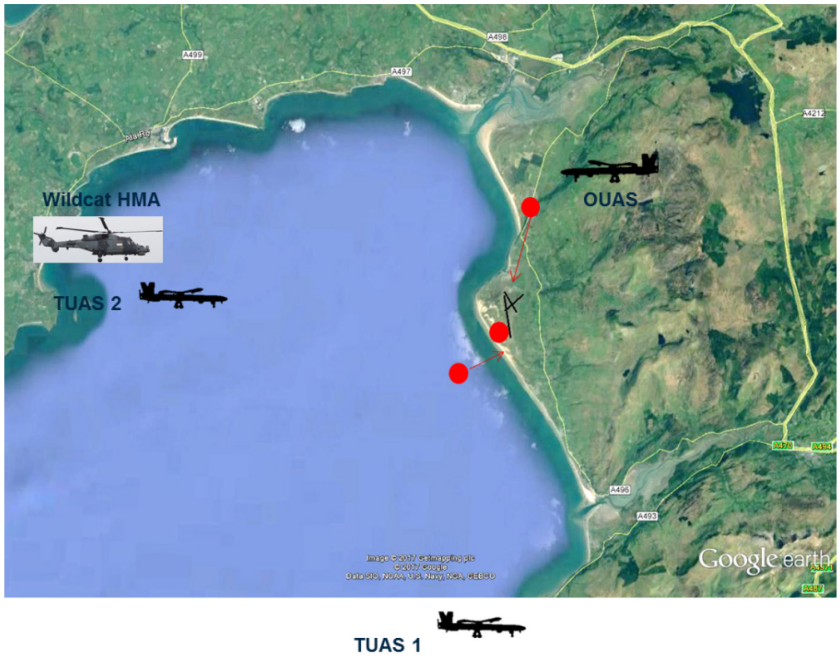

Figure 3-7: Use Case Two Map.

Enemy Forces include:

- Several arms caches; and
- One land vehicle.

The enemy force ground team penetrate the base perimeter in the south in order to attack and destroy base infrastructure and personnel. As part of the attack, other Enemy Forces attack base with a Vehicle-Borne Improvised Explosive Device (VBIED) at one of the gates.

Friendly Forces must locate and identify potential threats and react accordingly. This requires assessment of ISR data from multiple sources:

- COMINT (potentially linking EF troops to VBIED – coordination of attack);
- OUAS monitoring a suspect VBIED nearing the FOB (detail communicated over datalink);
- HMA and TUAS monitoring a suspect vessel heading towards coast near FOB; and
- SAR capture of FOB area.

SUAS can undertake surveillance and recce in reaction to the intelligence picture:

- Monitoring gates for VBIED approach (handing track of the VBIED to SUAS to release OUAS asset);
- Searching fence lines for EF incursions; and
- Overwatch of friendly troop patrols searching for EF incursion.

Fast Jet involvement may be required to provide a show of force over the suspect vessel (to deter landing) that may require teaming with TUAS (provision of still imagery for PID).

3.3.5 Use Case Three

Use Case Three is illustrated in Figure 3-8. Friendly Forces include:

- Helicopter Maritime Attack (HMA);
- Three Tactical Unmanned Air Systems (TUAS);
- One Small UAS;
- One Fast Air;
- One Support Helicopter;
- Foot Patrol; and
- One Operational UAS (OUAS).

Enemy Forces include:

- Several arms caches; and
- One land vehicle.

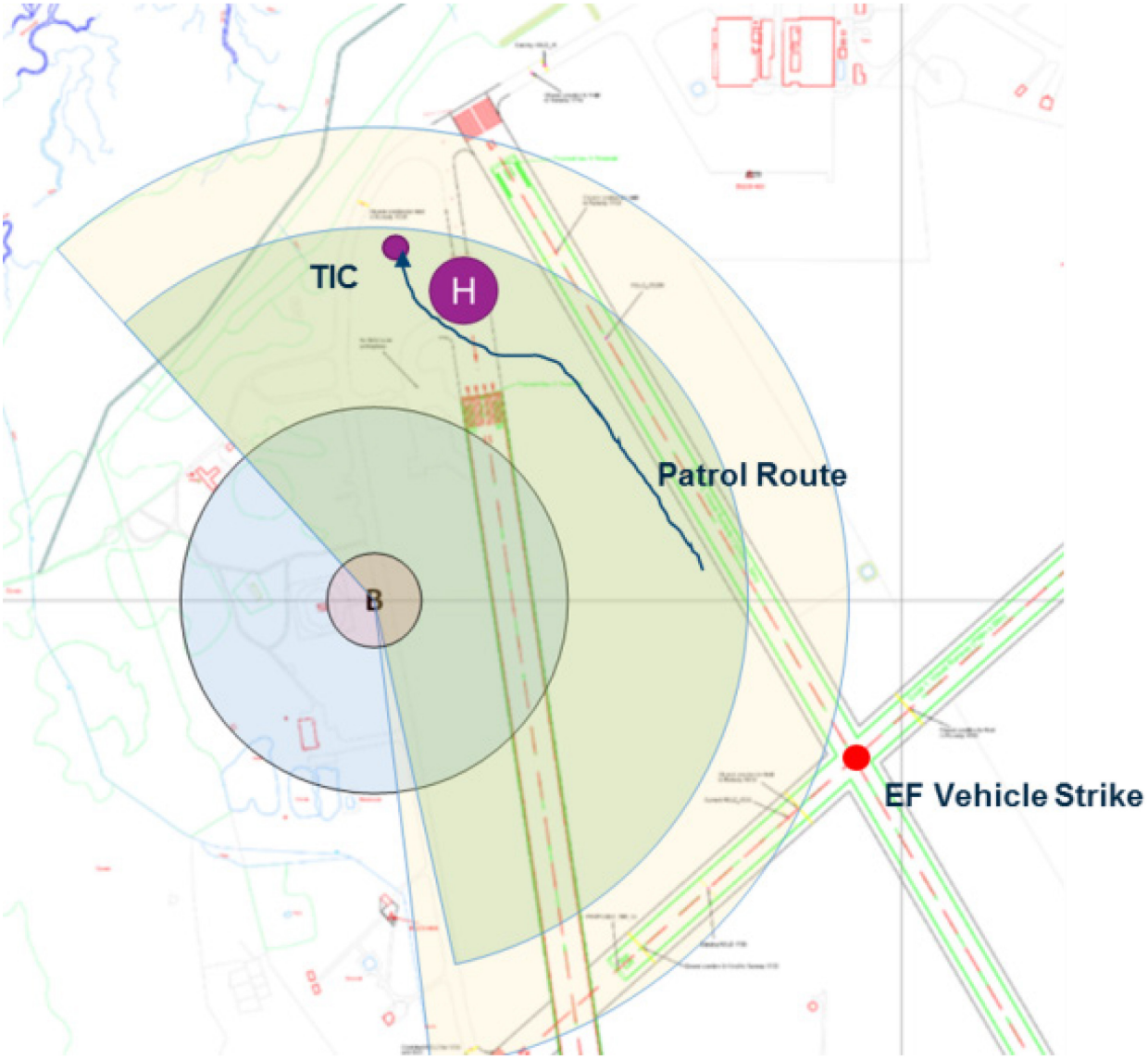

Figure 3-8: Use Case Three Map.

Having failed to use the VBIED, enemy forces replan their attack on the base. Calling in for additional equipment from the sea, enemy forces attempt to set IEDs at two different locations.

This Use Case focuses on the management of ISR assets when reacting to multiple events which occur within the base or outside or the base perimeter. This requires assessment of ISR data from multiple sources:

- COMINT may provide indication of a replan / enemy forces near coast;
- Maritime ISR provides indication of a vessel approaching the coast near the FOB;
- TUAS monitors movement of packages from vessel to a vehicle; and
- TUAS monitor EF Vehicle.

Having failed to use the VBIED, enemy forces replan their attack on the base. Calling in for additional equipment from the sea, enemy forces attempt to set IEDs at two different locations.

3.4 USE CASE ONE – ISR: APPLICATION AND BENEFIT

Table 3-1 is a summary of the utility (high, medium and low) for each TA or HAT Pattern. The following tables are a detailed input from each nation for Use Case One:

UK-1: HAT Collaborative Verification and Validation – Adaptable Autonomy and Policy Management: Development, Test and Evaluation (Table 3-2);

US-1: Task Management and Plan Monitoring (Table 3-3);

US-2: Intelligent Multi-Unmanned Vehicle Planner with Adaptive Collaborative Control Technologies (IMPACT) (Table 3-4);

US-3: Bi-Directional Communication (Table 3-5); and

US-4: Transparency (Table 3-6).

Table 3-1: Summary of the Utility (High, Medium and Low) for Each TA or HAT Pattern.

USE CASE 1: ISR						
USE CASE 1: SPECIFICS		**UK-1**	**US-1**	**US-2**	**US-3**	**US-4**
HUMINT	Human Intelligence is provided that indicates that an Enemy Force (EF) may attempt to recce the FOB in preparation for an attack. Enemy recce Force likely to attempt an insertion from the sea, coordinating with land-based local contacts.	**HIGH**	**HIGH**	**LOW**	**N/A**	**N/A**
ISR TASKING	ISR assets tasked to undertake perimeter and wider battlespace surveillance.	**HIGH**	**HIGH**	**HIGH**	**HIGH**	**HIGH**
COMINT	TUAS1 to undertake preplanned route circuit.	**HIGH**	**MED**	**N/A**	**LOW**	**HIGH**
SAR OF POTENTIAL BEACH LANDING SITES	TUAS 3 to gather SAR of potential beach areas where small craft could land personnel.	**HIGH**	**HIGH**	**MED**	**HIGH**	**HIGH**

USE CASE 1: ISR						
USE CASE 1: SPECIFICS		**UK-1**	**US-1**	**US-2**	**US-3**	**US-4**
MARITIME ISR – TEAMING HMA WITH TUAS	HMA and TUAS to operate within allocated search areas. HMA Operator to positively identify all surface vessels in the coastal region.	**HIGH**	**HIGH**	**N/A**	**HIGH**	**HIGH**
COMINT PF REPORT	EF vehicle in beach location. Occupant attempting communication/coordination with EF in boat.	**LOW**	**LOW**	**N/A**	**N/A**	**N/A**
MARITIME ISR – SUSPECT SURFACE VESSEL	HMA and TUAS team detect a boat operating outside of normal pattern of life. Closest TUAS is directed to get EO/IR for identification. TUAS with EO/IR track, HMA operator identifies as a suspect. Track is transiting towards coast, TUAS will either enter HMA Airspace or HMA takes over EO/IR track.	**HIGH**	**HIGH**	**MED**	**HIGH**	**HIGH**
SAR OF COMINT AREA	TUAS 3 is retasked to gather SAR imagery of location of COMINT.	**HIGH**	**HIGH**	**MED**	**HIGH**	**HIGH**
EF RECCE TEAM LITTORAL INSERTION	EF insertion team boat reaches shore line disembarking EF team who meet another EF personnel on beach.	**LOW**	**HIGH**	**N/A**	**N/A**	**N/A**
PID OF EF TEAM	EF Team members positively identified by intCell with access to EO/IR imagery from TUAS/HMA.	**LOW**	**MED**	**LOW**	**N/A**	**N/A**
TRACK EF TEAM	EF team leave area in vehicle, routing towards the FOB.	**HIGH**	**HIGH**	**MED**	**N/A**	**N/A**

Table 3-2: UK-1: HAT Collaborative Verification and Validation – Adaptable Autonomy and Policy Management: Development, Test and Evaluation.

TECHNICAL ACTIVITY: UK-1	
HAT Collaborative Verification and Validation *Adaptable Autonomy and Policy Management: Development, Test and Evaluation*	
ORIGINATING ORGANISATION	AUTHOR
QinetiQ	M. Thomas
DESCRIPTION:	
Adaptable Autonomy *with automated* ***Policy Management*** *functionality has been developed and tested within the UK Live, Virtual and Constructive environment to evaluate core mission enabling technologies underpinning the exploitation of* ***Human-Autonomy Teaming*** *with intelligent unmanned systems, including:* • *Situation Assessment Support System (SASS) used to monitor external and internal environments, assessing consequences and identifying appropriate courses of action.* • *Policy Management (PolMan) automation maintains a database of applicable policies which serves to ensure policy compliance, identifies policy violations and provides mitigations.* • *Conflict resolution; and* • *Negotiation.* • *Development and Management of Autonomy Behaviours.* • *Multi-Platform Task Scheduling;* • *SAR Tactics Planner;* • *Intelligent Routing and Hold Pattern Tactics; and* • *Multiple Search Tactics.* • *Manned Unmanned Teaming (MUMT).* • *Level of Interoperability control; and* • *Handover.*	
UTILITY AND MILITARY BENEFIT	
• AA, using SASS and Policy Management, alerts operators to potential violations and conflicts in applicable policies in the planning and execution of missions. • *Conflict Resolution mitigation includes recommendations for automated negotiations with relevant agencies.* • *Task scheduling and planning of multi-platform heterogeneous ISR assets. PolMan ensures plan deconfliction for multiple platforms and respective airspace allocations.* • *Policy Management ensures increased automation performance and trustworthiness through correct and timely usage of complex autonomy behaviours.* • *Increase decision speed (agility) and decision quality (adaptability) in multi-asset control and manned unmanned teaming.*	

USE CASE 1: ISR			
USE CASE 1: SPECIFICS		**UTILITY**	**APPLICATION AND BENEFIT**
HUMINT	Human Intelligence is provided that indicates that an Enemy Force (EF) may attempt to recce the FOB in preparation for an attack. Enemy recce Force likely to attempt an insertion from the sea, coordinating with land-based local contacts.	**HIGH**	*Pre-amble and set up of ISR picture to set the scene.*
ISR TASKING	ISR assets tasked to undertake perimeter and wider battlespace surveillance.	**HIGH**	*Task scheduling of UAS ISR assets. PolMan ensures plan deconfliction for multiple platforms and respective airspace allocations.*
COMINT	TUAS1 to undertake preplanned route circuit.	**HIGH**	*PolMan, combining SASS, ensures UAS complies with route plan. Any deviations alerted to operator to correct.*
SAR OF POTENTIAL BEACH LANDING SITES	TUAS 3 to gather SAR of potential beach areas where small craft could land personnel.	**HIGH**	*PolMan ensuring correct application of autonomy behaviours to develop TTP compliant SAR plans.*
MARITIME ISR – TEAMING HMA WITH TUAS	HMA and TUAS to operate within allocated search areas. HMA Operator to positively identify all surface vessels in the coastal region.	**HIGH**	*SASS, PolMan and MUMT functionality supports operator SA in undertaking complex multi-platform coordination and control.*
COMINT PF REPORT	EF vehicle in beach location. Occupant attempting communication/coordination with EF in boat.	**LOW**	*Application of autonomy behaviours for ISR assets maintaining track. SASS using PolMan ensures continued deconfliction from other assets.*
MARITIME ISR – SUSPECT SURFACE VESSEL	HMA and TUAS team detect a boat operating outside of normal pattern of life. Closest TUAS is directed to get EO/IR for identification. TUAS with EO/IR track, HMA operator identifies as a suspect. Track is transiting towards coast, TUAS will either enter HMA Airspace or HMA takes over EO/IR track.	**HIGH**	*SASS, using PolMan, alerts operators to potential airspace policy conflicts. Conflict Resolution includes recommendations for airspace negotiations, which can be automated (system to remote system, or system to remote operator).*

USE CASE 1: ISR			
USE CASE 1: SPECIFICS		**UTILITY**	**APPLICATION AND BENEFIT**
SAR OF COMINT AREA	TUAS 3 is retasked to gather SAR imagery of location of COMINT.	**HIGH**	*Task scheduling and PolMan to direct application of correct autonomy behaviours to develop TTP compliant SAR plans.*
EF RECCE TEAM LITTORAL INSERTION	EF insertion team boat reaches shore line disembarking EF team who meet another EF personnel on beach.	**LOW**	*Application of autonomy behaviours for ISR assets maintaining track. SASS using PolMan ensures continued deconfliction from other assets.*
PID OF EF TEAM	EF Team members positively identified by intCell with access to EO/IR imagery from TUAS/HMA.	**LOW**	*Application of autonomy behaviours for ISR assets maintaining track. SASS using PolMan ensures continued deconfliction from other assets.*
TRACK EF TEAM	EF team leave area in vehicle, routing towards the FOB.	**HIGH**	*Application of autonomy behaviours for ISR assets maintaining track. SASS using PolMan ensures continued deconfliction from other assets. SASS directs need for task scheduling and PolMan for policy compliance for retasked assets.*

PRINCIPAL MISSION RISK					
Risks on not using PolMan to manage and control automation and autonomy include operations not being militarily effective and not complying with applicable TTPs and higher-level regulatory governance.					
PROBABILITY	EXTREMELY IMPROBABLE	IMPROBABLE	REMOTE	**OCCASIONAL**	FREQUENT
SEVERITY	CATASTROPHIC	SEVERE	**MAJOR**	MINOR	NEGLIGIBLE

COMMENTS
Without SASS and PolMan, there is a dependency on the unreliable human supervisory role to be policy aware for all aspects of multi-platform coordination and control missions.
Not deemed to be a Safety Critical issue (catastrophic or severe), but is a mission critical (major) function.

OTHER MISSION RISKS
Not completing tasks effectively.
Loss of automation/autonomy operator trust.
Adversely effecting other task lines (platform operators).

REFERENCES [18], [19], [20].

Table 3-3: US-1: Task Management and Plan Monitoring.

TECHNICAL ACTIVITY: US-1	
Task Management and Plan Monitoring	
ORIGINATING ORGANISATION	AUTHOR
Space and Naval Warfare Systems Center Pacific	*Doug Lange*
DESCRIPTION:	
The task manager capable of determining user tasks, dividing tasks into a hierarchy, presenting tasks to the user, and providing a mechanism to execute an action for each task. It is intended to allow a human operator to work in a complex environment and provide for some task load balancing between the human and autonomous assistants. *Plan monitor evaluates the progress of the execution of plans and utilises strategies for correcting problems. These can include fully autonomous strategies, or those that involve the human operator.*	
UTILITY AND MILITARY BENEFIT	
Complex environments with large numbers of plans being executed simultaneously put a burden on human operators. TM and PM team with the human to allow for better command and control of the available forces and over the tactical situation.	

USE CASE 1: ISR			
USE CASE 1: SPECIFICS		**UTILITY**	**APPLICATION AND BENEFIT**
HUMINT	Human Intelligence is provided that indicates that an Enemy Force (EF) may attempt to recce the FOB in preparation for an attack. Enemy recce Force likely to attempt an insertion from the sea, coordinating with land-based local contacts.	**HIGH**	
ISR TASKING	ISR assets tasked to undertake perimeter and wider battlespace surveillance.	**HIGH**	
COMINT	TUAS1 to undertake preplanned route circuit.	**MED**	
SAR OF POTENTIAL BEACH LANDING SITES	TUAS 3 to gather SAR of potential beach areas where small craft could land personnel.	**HIGH**	
MARITIME ISR – TEAMING HMA WITH TUAS	HMA and TUAS to operate within allocated search areas. HMA Operator to positively identify all surface vessels in the coastal region.	**HIGH**	

USE CASE 1: ISR			
USE CASE 1: SPECIFICS		**UTILITY**	**APPLICATION AND BENEFIT**
MARITIME ISR – TEAMING HMA WITH TUAS	HMA and TUAS to operate within allocated search areas. HMA Operator to positively identify all surface vessels in the coastal region.	**HIGH**	
COMINT PF REPORT	EF vehicle in beach location. Occupant attempting communication/coordination with EF in boat.	**LOW**	
MARITIME ISR – SUSPECT SURFACE VESSEL	HMA and TUAS team detect a boat operating outside of normal pattern of life. Closest TUAS is directed to get EO/IR for identification. TUAS with EO/IR track, HMA operator identifies as a suspect. Track is transiting towards coast, TUAS will either enter HMA Airspace or HMA takes over EO/IR track.	**HIGH**	
SAR OF COMINT AREA	TUAS 3 is retasked to gather SAR imagery of location of COMINT.	**HIGH**	
EF RECCE TEAM LITTORAL INSERTION	EF insertion team boat reaches shore line disembarking EF team who meet another EF personnel on beach.	**HIGH**	
PID OF EF TEAM	EF Team members positively identified by intCell with access to EO/IR imagery from TUAS/HMA.	**MED**	
TRACK EF TEAM	EF team leave area in vehicle, routing towards the FOB.	**HIGH**	

PRINCIPAL MISSION RISK					
PROBABILITY	EXTREMELY IMPROBABLE	IMPROBABLE	REMOTE	OCCASIONAL	**FREQUENT**
SEVERITY	CATASTROPHIC	**SEVERE**	MAJOR	MINOR	NEGLIGIBLE

COMMENTS
TM and PM become important in high complexity environments. Each of the use cases above provide little challenge on their own. It is the combination of all of them occurring within a scenario that provides the requisite complexity. Operators found this level of scenario difficult without TM and PM, and yet this is not an overly complex scenario. Therefore, in scenarios at this level of complexity or higher there are frequently situations where these capabilities are important and the severity of not having them can be severe.

Table 3-4: US-2: Intelligent Multi-Unmanned Vehicle Planner with Adaptive Collaborative Control Technologies (IMPACT).

TECHNICAL ACTIVITY: US-2	
INTELLIGENT MULTI-UNMANNED VEHICLE PLANNER WITH ADAPTIVE COLLABORATIVE CONTROL TECHNOLOGIES (IMPACT)	
ORIGINATING ORGANISATION	AUTHOR
AFRL/711HPW	*Mark Draper*
DESCRIPTION:	
Agility in tactical decision making and mission management is a key attribute for enabling teams of heterogeneous Unmanned Vehicles (UxV) to successfully manage the "fog of war" with its inherently complex, ambiguous, and time-challenging conditions. This agility requires effective operator-autonomy teaming including the achievement of trusted collaboration and the flexible, high-level tasking required for team task sharing and decision superiority. A tri-service team within the US has conducted research focused on instantiating an "Intelligent Multi-UxV Planner with Adaptive Collaborative/Control Technologies" (IMPACT) by combining flexible play calling for task delegation, bi-directional human-autonomy interaction, advanced cooperative control algorithms, intelligent agent reasoning, and autonomic technologies to enable effective single operator Command and Control (C2) of cooperative multi-UxV missions. An IMPACT operator, with intelligent assistance, was able to dynamically task and manage a total of 12 UxV (four air, four ground, and four sea surface vehicles) in response to several unexpected events that arose during an ongoing base perimeter defence mission.	
UTILITY AND MILITARY BENEFIT	
Note that it is envisioned that IMPACT capabilities could support all these Use Cases by providing single operator tactical C2 of multiple UxVs in support of planned and new tasking. *Improved human effectiveness:* • *Dynamically managed workload while supervising multiple assets; faster and more accurate decisions.* *Increased automation performance/trustworthiness:* • *Enhanced performance via auto-monitoring of play execution with repair strategies for contingencies.* *Enhanced human-autonomy teaming:* • *Bi-directional comms, prioritised courses of action and task assignment, agile and flexible levels of control.* *Operational applications of anticipated utility:* • *C2, ISR, Agile Combat Support, Special operations, Resupply, etc.* *Operational benefits:* • *Force multiplication, reduced risk to humans, reduced manpower needs, optimised operator performance, increased collaboration, increased operational flexibility, agility and adaptability.*	

USE CASE 1: ISR			
USE CASE 1: SPECIFICS		**UTILITY**	**APPLICATION AND BENEFIT**
HUMINT	Human Intelligence is provided that indicates that an Enemy Force (EF) may attempt to recce the FOB in preparation for an attack. Enemy recce Force likely to attempt an insertion from the sea, coordinating with land-based local contacts.	**LOW**	*Info feed into IMPACT system.*
ISR TASKING	ISR assets tasked to undertake perimeter and wider battlespace surveillance.	**HIGH**	*Constantly updated background behaviour optimisation.*
COMINT	TUAS1 to undertake preplanned route circuit.	**N/A**	
SAR OF POTENTIAL BEACH LANDING SITES	TUAS 3 to gather SAR of potential beach areas where small craft could land personnel.	**MED**	*Added specialized sensors could be used to determine this, and if they exist on small UAS then they can be tasked by IMPACT.*
MARITIME ISR – TEAMING HMA WITH TUAS	HMA and TUAS to operate within allocated search areas. HMA Operator to positively identify all surface vessels in the coastal region.	**N/A**	
COMINT PF REPORT	EF vehicle in beach location. Occupant attempting communication/coordination with EF in boat.	**N/A**	
MARITIME ISR – SUSPECT SURFACE VESSEL	HMA and TUAS team detect a boat operating outside of normal pattern of life. Closest TUAS is directed to get EO/IR for identification. TUAS with EO/IR track, HMA operator identifies as a suspect. Track is transiting towards coast, TUAS will either enter HMA Airspace or HMA takes over EO/IR track.	**MED**	*IMPACT can direct the TUAS to investigate through operator or agent-directed tasking.*
SAR OF COMINT AREA	TUAS 3 is retasked to gather SAR imagery of location of COMINT.	**MED**	*IMPACT can task delegate via a play.*

USE CASE 1: ISR			
USE CASE 1: SPECIFICS		**UTILITY**	**APPLICATION AND BENEFIT**
EF RECCE TEAM LITTORAL INSERTION	EF insertion team boat reaches shore line disembarking EF team who meet another EF personnel on beach.	**N/A**	
PID OF EF TEAM	EF Team members positively identified by intCell with access to EO/IR imagery from TUAS/HMA.	**LOW**	*PID is external to IMPACT.*
TRACK EF TEAM	EF team leave area in vehicle, routing towards the FOB.	**MED**	*Call tracking play, optimise remaining vehicles towards normal full coverage background behaviour.*

PRINCIPAL MISSION RISK
If using IMPACT, need to guard against cyber threats that could spoof or deny C2 from this critical node. Also, will require a separate sensor management capability as IMPACT focuses on C2. *If not using IMPACT, possibility of reduced coordination/collaboration efficiency due to extra comms requirements associated with coordinating multiple UxV operators.*

PROBABILITY	EXTREMELY IMPROBABLE	IMPROBABLE	REMOTE	OCCASIONAL	FREQUENT
SEVERITY	CATASTROPHIC	SEVERE	MAJOR	MINOR	NEGLIGIBLE

COMMENTS

Table 3-5: US-3: Bi-Directional Communication.

TECHNICAL ACTIVITY: US-3	
Bi-Directional Communication	
ORIGINATING ORGANISATION	AUTHOR
NASA	*Jay Shively*
DESCRIPTION:	
UTILITY AND MILITARY BENEFIT	

USE CASE 1: ISR			
USE CASE 1: SPECIFICS		**UTILITY**	**APPLICATION AND BENEFIT**
HUMINT	Human Intelligence is provided that indicates that an Enemy Force (EF) may attempt to recce the FOB in preparation for an attack. Enemy recce Force likely to attempt an insertion from the sea, coordinating with land-based local contacts.	**N/A**	
ISR TASKING	ISR assets tasked to undertake perimeter and wider battlespace surveillance.	**HIGH**	
COMINT	TUAS1 to undertake preplanned route circuit.	**LOW**	
SAR OF POTENTIAL BEACH LANDING SITES	TUAS 3 to gather SAR of potential beach areas where small craft could land personnel.	**HIGH**	
MARITIME ISR – TEAMING HMA WITH TUAS	HMA and TUAS to operate within allocated search areas. HMA Operator to positively identify all surface vessels in the coastal region.	**HIGH**	

USE CASE 1: ISR			
USE CASE 1: SPECIFICS		**UTILITY**	**APPLICATION AND BENEFIT**
COMINT PF REPORT	EF vehicle in beach location. Occupant attempting communication/coordination with EF in boat.	**N/A**	
MARITIME ISR – SUSPECT SURFACE VESSEL	HMA and TUAS team detect a boat operating outside of normal pattern of life. Closest TUAS is directed to get EO/IR for identification. TUAS with EO/IR track, HMA operator identifies as a suspect. Track is transiting towards coast, TUAS will either enter HMA Airspace or HMA takes over EO/IR track.	**HIGH**	
SAR OF COMINT AREA	TUAS 3 is retasked to gather SAR imagery of location of COMINT.	**HIGH**	
EF RECCE TEAM LITTORAL INSERTION	EF insertion team boat reaches shore line disembarking EF team who meet another EF personnel on beach.	**N/A**	
PID OF EF TEAM	EF Team members positively identified by intCell with access to EO/IR imagery from TUAS/HMA.	**N/A**	
TRACK EF TEAM	EF team leave area in vehicle, routing towards the FOB.	**N/A**	

PRINCIPAL MISSION RISK
The ability to communicate and query the automated team members ensures better understanding of the system and more accurately calibrated trust. This incurs the risk of mode confusions, over-or-under reliance on the systems.

PROBABILITY	EXTREMELY IMPROBABLE	IMPROBABLE	REMOTE	**OCCASIONAL**	FREQUENT
SEVERITY	CATASTROPHIC	SEVERE	**MAJOR**	MINOR	NEGLIGIBLE

COMMENTS

Table 3-6: US-4: Transparency.

TECHNICAL ACTIVITY: US-4 – HAT DESIGN PATTERN	
Transparency	
ORIGINATING ORGANISATION	AUTHOR
US Army Research Laboratory	Jessie Chen and Michael Barnes
DESCRIPTION:	
The goal of the Transparency Pattern is to provide a general human-machine interface design solution to support human-agent communications in order to achieve joint decision-making effectiveness. Drawing inspiration from Endsley's three levels of SA – perception, comprehension, and projection – the ***Situation Awareness-Based Agent Transparency*** *(SAT) model describes the information that agents need to convey about their decision-making process in order to facilitate the shared understanding required to perform effective human-agent teamwork. More specifically, the pattern describes the information requirement from the agent to support the human's awareness of the agent's:* *1) Current actions and plans;* *2) Reasoning process; and* *3) Outcome predictions and uncertainty.* *The Transparency Pattern based on the SAT model can be applied to a wide variety of human-machine interfaces, where the agent's reasoning information and projections of future outcomes (including uncertainty) are important to its/his/her team members (humans or machines).*	
UTILITY AND MILITARY BENEFIT	
The SAT model provides a useful framework for organising the information requirements related to agent transparency. More specifically, transparency on the part of the agent supports the human's: situation awareness regarding the agent, decision making and thus overall human-agent team performance, as well as trust calibration process (i.e., accepting the agent's plan when it is correct and rejecting it when it is incorrect). The benefits of the Transparency Pattern includes: improved human effectiveness (human-in-the-loop control and command authority), increased automation performance and trustworthiness (agents can be utilised optimally based on their capabilities due to their greater predictability and understandability to the humans), and enhanced human-autonomy teaming (communication, coordination, cooperation, collaboration, and adaptivity). The Transparency Pattern is anticipated to be particularly useful for C2-related applications and missions involving Intelligent Agents (IAs). The anticipated operational benefits include: optimised operator performance, reduced training requirements, improved contingency management, increased operational flexibility, agility and adaptability. Because of the complexity of the ISR mission, it could only be accomplished by increasing manpower or with IA assistance. However, the human must have situation awareness of the mission and of the IA in order to ensure mission success.	

USE CASE 1: ISR			
USE CASE 1: SPECIFICS		**UTILITY**	**APPLICATION AND BENEFIT**
HUMINT	Human Intelligence is provided that indicates that an Enemy Force (EF) may attempt to recce the FOB in preparation for an attack. Enemy recce Force likely to attempt an insertion from the sea, coordinating with land-based local contacts.	**N/A**	
ISR TASKING	ISR assets tasked to undertake perimeter and wider battlespace surveillance.	**HIGH**	*Assets indicating their 1) Current actions and plans; 2) Reasoning process; and 3) Outcome predictions and uncertainty.*
COMINT	TUAS1 to undertake preplanned route circuit.	**HIGH**	*TUAS indicating its 1) Current actions and plans; 2) Reasoning process; and 3) Outcome predictions and uncertainty.*
SAR OF POTENTIAL BEACH LANDING SITES	TUAS 3 to gather SAR of potential beach areas where small craft could land personnel.	**HIGH**	*TUAS indicating its 1) Current actions and plans; 2) Reasoning process; and 3) Outcome predictions and uncertainty.*
MARITIME ISR – TEAMING HMA WITH TUAS	HMA and TUAS to operate within allocated search areas. HMA Operator to positively identify all surface vessels in the coastal region.	**HIGH**	*TUAS indicating its 1) Current actions and plans; 2) Reasoning process; and 3) Outcome predictions and uncertainty.*
COMINT PF REPORT	EF vehicle in beach location. Occupant attempting communication/coordination with EF in boat.	**N/A**	
MARITIME ISR – SUSPECT SURFACE VESSEL	HMA and TUAS team detect a boat operating outside of normal pattern of life. Closest TUAS is directed to get EO/IR for identification. TUAS with EO/IR track, HMA operator identifies as a suspect. Track is transiting towards coast, TUAS will either enter HMA Airspace or HMA takes over EO/IR track.	**HIGH**	*TUAS indicating its 1) Current actions and plans; 2) Reasoning process; and 3) Outcome predictions and uncertainty.*

USE CASE 1: ISR			
USE CASE 1: SPECIFICS		**UTILITY**	**APPLICATION AND BENEFIT**
SAR OF COMINT AREA	TUAS 3 is retasked to gather SAR imagery of location of COMINT.	**HIGH**	*TUAS indicating its 1) Current actions and plans; 2) Reasoning process; and 3) Outcome predictions and uncertainty.*
EF RECCE TEAM LITTORAL INSERTION	EF insertion team boat reaches shore line disembarking EF team who meet another EF personnel on beach.	**N/A**	
PID OF EF TEAM	EF Team members positively identified by intCell with access to EO/IR imagery from TUAS/HMA.	**N/A**	
TRACK EF TEAM	EF team leave area in vehicle, routing towards the FOB.	**N/A**	

PRINCIPAL MISSION RISK
Mission risks of not using the Transparency Pattern include: degraded human operator's situation awareness of the agents' (ISR assets and TUASs) current actions and plans, reasoning process, projected outcomes and uncertainty; suboptimal decision making on the part of the human operator due to his/her understanding of the agents (e.g., disuse or misuse of the agent); increased operator workload due to the needs for the human to understand the agents' behaviours.

PROBABILITY	EXTREMELY IMPROBABLE	IMPROBABLE	REMOTE	OCCASIONAL	**FREQUENT**
SEVERITY	CATASTROPHIC	**SEVERE**	MAJOR	MINOR	NEGLIGIBLE

COMMENTS

OTHER MISSION RISKS

REFERENCES [21], [22]

3.5 USE CASE TWO – BASE PROTECTION: APPLICATION AND BENEFIT

Table 3-7 is a summary of the utility (high, medium and low) for each TA or HAT Pattern. The following tables are a detailed input from each nation for Use Case Two:

UK-1: HAT Collaborative Verification and Validation – Adaptable Autonomy and Policy Management: Development, Test and Evaluation (Table 3-8);

US-1: Task Management and Plan Monitoring (Table 3-9);

US-2: Intelligent Multi-Unmanned Vehicle Planner with Adaptive Collaborative Control Technologies (IMPACT) (Table 3-10);

US-3: Bi-Directional Communication (Table 3-11); and

US-4: Transparency (Table 3-12).

Table 3-7: Summary of the Utility (High, Medium and Low) for Each TA or HAT Pattern.

USE CASE 2: BASE PROTECTION						
USE CASE 2: SPECIFICS		**UK-1**	**US-1**	**US-2**	**US-3**	**US-4**
LOST EF	On the approach to the FOB, the EF is lost.	**N/A**	**HIGH**	**N/A**	**N/A**	**N/A**
COMINT (EF COORD)	COMINT is detected very close to the FOB. Indications are that this could lead to a coordinated attack on the FOB that may include a perimeter breach or a Vehicle-Borne IED (VBIED) strike.	**HIGH**	**HIGH**	**HIGH**	**N/A**	**N/A**
VBIED SEARCH (TUAS/HMA) AND VBIED TRACK BY OUAS	TUAS and SUAS assets engaged on searching the base and the area around the base. Over SATCOM, OUAS track of a suspect vehicle heading towards the base is reported.	**HIGH**	**HIGH**	**HIGH**	**MED**	**HIGH**
MARITIME ISR DETECT	Teamed HMA and TUAS conducting maritime ISR detect a vessel operating outside of POL and is heading towards beach near FOB.	**LOW/ MED/ HIGH/ N/A**	**HIGH**	**MED**	**MED**	**HIGH**
VBIED TRACK/HANDOVER ->SUAS	SUAS asset is tasked with picking up the suspect vehicle (VBIED).	**HIGH**	**HIGH**	**N/A**	**LOW**	**HIGH**

USE CASE 2: BASE PROTECTION						
USE CASE 2: SPECIFICS		**UK-1**	**US-1**	**US-2**	**US-3**	**US-4**
STOP VBIED	The suspect vehicle is stopped at the main gate (no detonation).	**LOW**	**MED**	**N/A**	**N/A**	**N/A**
EF PENETRATION OF FOB PERIMETER	Whilst there is activity at the main gate, the EF team manage to penetrate the Base fence perimeter.	**LOW**	**HIGH**	**LOW**	**N/A**	**N/A**
SEARCH/FIND EF TEAM NEAR BASE PERIMETER (TUAS/SUAS)	The EF penetration is reported and base ISR assets directed to find the EF team.	**HIGH**	**HIGH**	**HIGH**	**N/A**	**MED**
PID/FIX	Upon finding the EF team, they are positively identified by SUAS.	**HIGH**	**MED**	**N/A**	**HIGH**	**HIGH**
SEND FOOT PATROL AND CAPTURE	SUAS to provide overwatch of friendly force foot patrol sent in to capture EF.	**HIGH**	**HIGH**	**MED**	**MED**	**HIGH**
EF PICKUP BOAT (TUAS) – STRIKE / SHOW OF FORCE	The vessel being tracked by the HMA/TUAS team is identified as a potential pick up for the EF team. A show of force is requested to deter the vessel from nearing the coast.	**HIGH**	**HIGH**	**MED**	**MED**	**HIGH**

Table 3-8: UK-1: HAT Collaborative Verification and Validation – Adaptable Autonomy and Policy Management: Development, Test and Evaluation.

TECHNICAL ACTIVITY: UK-1	
HAT Collaborative Verification and Validation *Adaptable Autonomy and Policy Management: Development, Test and Evaluation*	
ORIGINATING ORGANISATION	AUTHOR
QinetiQ	M Thomas
DESCRIPTION:	

Adaptable Autonomy *with automated* ***Policy Management*** *functionality has been developed and tested within the UK Live, Virtual and Constructive environment to evaluate core mission enabling technologies underpinning the exploitation of* ***Human-Autonomy Teaming*** *with intelligent unmanned systems, including:*
• *Situation Assessment Support System (SASS) used to monitor external and internal environments, assessing consequences and identifying appropriate courses of action.*
• *Policy Management (PolMan) automation maintains a database of applicable policies which serves to ensure policy compliance, identifies policy violations and provides mitigations.*
  • *Conflict resolution; and*
  • *Negotiation.*
• *Development and Management of Autonomy Behaviours.*
  • *Multi-Platform Task Scheduling;*
  • *SAR Tactics Planner;*
  • *Intelligent Routing and Hold Pattern Tactics; and*
  • *Multiple Search Tactics.*
• *Manned Unmanned Teaming (MUMT).*
  • *Level of Interoperability control; and*
  • *Handover.*	

UTILITY AND MILITARY BENEFIT	
• *AA, using SASS and Policy Management, alerts operators to potential violations and conflicts in applicable policies in the planning and execution of missions.* • *Conflict Resolution mitigation includes recommendations for automated negotiations with relevant agencies.* • *Task scheduling and planning of multi-platform heterogeneous ISR assets. PolMan ensures plan deconfliction for multiple platforms and respective airspace allocations.* • *Policy Management ensures increased automation performance and trustworthiness through correct and timely usage of complex autonomy behaviours.* • *Increase decision speed (agility) and decision quality (adaptability) in multi-asset control and manned-unmanned teaming.*	

USE CASE 2: BASE PROTECTION			
USE CASE 2: SPECIFICS		**UTILITY**	**APPLICATION AND BENEFIT**
LOST EF	On the approach to the FOB, the EF is lost.	**N/A**	*Pre-amble and set up use case.*
COMINT (EF COORD)	COMINT is detected very close to the FOB. Indications are that this could lead to a coordinated attack on the FOB that may include a perimeter breach or a Vehicle-Borne IED (VBIED) strike.	**HIGH**	*PolMan, combining SASS, ensures COMINT UAS complies with route plan. Any deviations alerted to operator to correct.*
VBIED SEARCH (TUAS/HMA) AND VBIED TRACK BY OUAS	TUAS and SUAS assets engaged on searching the base and the area around the base. Over SATCOM, OUAS track of a suspect vehicle heading towards the base is reported.	**HIGH**	*Task scheduling and PolMan to direct application of correct autonomy behaviours to develop effective search plans compliant to localised airspace constraints.* *SASS, using PolMan, alerts operators to potential airspace policy conflicts with non-organic (to the base) UAS assets. Conflict Resolution includes recommendations for airspace or track handover negotiations, which can be automated.*
MARITIME ISR DETECT	Teamed HMA and TUAS conducting maritime ISR detect a vessel operating outside of POL and is heading towards beach near FOB.	**HIGH**	*SASS, using PolMan, alerts operators to potential airspace policy conflicts. Conflict Resolution includes recommendations for airspace negotiations, which can be automated (system to remote system, or system to remote operator).*
VBIED TRACK/HANDOVER ->SUAS	SUAS asset is tasked with picking up the suspect vehicle (VBIED).	**HIGH**	*Task scheduling and PolMan to direct application of correct autonomy behaviours for SUAS to takeover track whilst operating within constrained base airspace restrictions.*

USE CASE 2: BASE PROTECTION			
USE CASE 2: SPECIFICS		**UTILITY**	**APPLICATION AND BENEFIT**
STOP VBIED	The suspect vehicle is stopped at the main gate (no detonation).	**LOW**	*SASS, using PolMan, alerts operators to potential airspace policy conflicts by the SUAS.*
EF PENETRATION OF FOB PERIMETER	Whilst there is activity at the main gate, the EF team manage to penetrate the Base fence perimeter.	**LOW**	*SASS, using PolMan, alerts operators to potential airspace policy conflicts by the SUAS.*
SEARCH/FIND EF TEAM NEAR BASE PERIMETER (TUAS/SUAS)	The EF penetration is reported and base ISR assets directed to find the EF team.	**HIGH**	*Task scheduling and PolMan to maximise UAS assets and direct application of correct autonomy behaviours for multiple SUAS undertaking different tasks.*
PID/FIX	Upon finding the EF team, they are positively identified by SUAS.	**HIGH**	*SASS, using PolMan, alerts operators to potential airspace policy conflicts by the SUAS.*
SEND FOOT PATROL AND CAPTURE	SUAS to provide overwatch of friendly force foot patrol sent in to capture EF.	**HIGH**	*Task scheduling and PolMan to maximise UAS assets and direct application of correct autonomy behaviours for multiple SUAS undertaking different tasks maintain airspace deconfliction.*
EF PICKUP BOAT (TUAS) – STRIKE/SHOW OF FORCE	The vessel being tracked by the HMA/TUAS team is identified as a potential pick up for the EF team. A show of force is requested to deter the vessel from nearing the coast.	**HIGH**	*SASS, using PolMan, alerts operators to potential airspace policy conflicts. Conflict Resolution includes recommendations for airspace negotiations, which can be automated (system to remote system, or system to remote operator).*

PRINCIPAL MISSION RISK					
Risks on not using PolMan and automated negotiation to support Airspace Management adds to operator workload and increases likelihood of airspace conflicts.					
PROBABILITY	EXTREMELY IMPROBABLE	IMPROBABLE	REMOTE	**OCCASIONAL**	FREQUENT
SEVERITY	CATASTROPHIC	**SEVERE**	MAJOR	MINOR	NEGLIGIBLE

COMMENTS
Without SASS, PolMan and automated negotiations, there is a dependency on the unreliable human supervisory role to be aware for all task and dynamic airspace conflicts, requiring manual intervention to manage airspace access and restrictions, and platform deconflictions. *Could be deemed to be a Safety Critical issue (severe) if there is a risk of SUAS collision in confined airspace zones (SUAS Keep in Zones ~ 500 m).*
OTHER MISSION RISKS
Not completing tasks effectively – suboptimal search plans. *Loss of automation/autonomy operator trust.* *Adversely effecting other task lines (platform operators).*
REFERENCES [18], [19], [20].

Table 3-9: US-1: Task Management and Plan Monitoring.

TECHNICAL ACTIVITY: US-1	
Task Management and Plan Monitoring	
ORIGINATING ORGANISATION	AUTHOR
Space and Naval Warfare Systems Center Pacific	*Doug Lange*
DESCRIPTION:	
The task manager capable of determining user tasks, dividing tasks into a hierarchy, presenting tasks to the user, and providing a mechanism to execute an action for each task. It is intended to allow a human operator to work in a complex environment and provide for some task load balancing between the human and autonomous assistants. *Plan monitor evaluates the progress of the execution of plans and utilises strategies for correcting problems. These can include fully autonomous strategies, or those that involve the human operator.*	
UTILITY AND MILITARY BENEFIT	
Complex environments with large numbers of plans being executed simultaneously put a burden on human operators. TM and PM team with the human to allow for better command and control of the available forces and over the tactical situation.	

USE CASE 2: BASE PROTECTION			
USE CASE 2: SPECIFICS		**UTILITY**	**APPLICATION AND BENEFIT**
LOST EF	On the approach to the FOB, the EF is lost.	**HIGH**	
COMINT (EF COORD)	COMINT is detected very close to the FOB. Indications are that this could lead to a coordinated attack on the FOB that may include a perimeter breach or a Vehicle-Borne IED (VBIED) strike.	**HIGH**	
VBIED SEARCH (TUAS/HMA) AND VBIED TRACK BY OUAS	TUAS and SUAS assets engaged on searching the base and the area around the base. Over SATCOM, OUAS track of a suspect vehicle heading towards the base is reported.	**HIGH**	
MARITIME ISR DETECT	Teamed HMA and TUAS conducting maritime ISR detect a vessel operating outside of POL and is heading towards beach near FOB.	**HIGH**	

USE CASE 2: BASE PROTECTION			
USE CASE 2: SPECIFICS		**UTILITY**	**APPLICATION AND BENEFIT**
VBIED TRACK/ HANDOVER ->SUAS	SUAS asset is tasked with picking up the suspect vehicle (VBIED).	**HIGH**	
STOP VBIED	The suspect vehicle is stopped at the main gate (no detonation).	**MED**	
EF PENETRATION OF FOB PERIMETER	Whilst there is activity at the main gate, the EF team manage to penetrate the Base fence perimeter.	**HIGH**	
SEARCH/FIND EF TEAM NEAR BASE PERIMETER (TUAS/SUAS)	The EF penetration is reported and base ISR assets directed to find the EF team.	**HIGH**	
PID/FIX	Upon finding the EF team, they are positively identified by SUAS.	**MED**	
SEND FOOT PATROL AND CAPTURE	SUAS to provide overwatch of friendly force foot patrol sent in to capture EF.	**HIGH**	
EF PICKUP BOAT (TUAS) – STRIKE / SHOW OF FORCE	The vessel being tracked by the HMA/TUAS team is identified as a potential pick up for the EF team. A show of force is requested to deter the vessel from nearing the coast.	**HIGH**	

PRINCIPAL MISSION RISK					
Describe a mission risk of using or not using your TA or HAT Pattern then indicate the probability and severity and comment.					
PROBABILITY	EXTREMELY IMPROBABLE	IMPROBABLE	REMOTE	OCC ASIO NAL	**FREQUENT**
SEVERITY	CATASTROPHIC	**SEVERE**	MAJOR	MIN OR	NEGLIGIBLE

COMMENTS
TM and PM become important in high complexity environments. Each of the use cases above provide little challenge on their own. It is the combination of all of them occurring within a scenario that provides the requisite complexity. Operators found this level of scenario difficult without TM and PM, and yet this is not an overly complex scenario. Therefore, in scenarios at this level of complexity or higher there are frequently situations where these capabilities are important and the severity of not having them can be severe.

Table 3-10: US-2: Intelligent Multi-Unmanned Vehicle Planner with Adaptive Collaborative Control Technologies (IMPACT).

TECHNICAL ACTIVITY: US-2	
INTELLIGENT MULTI-UNMANNED VEHICLE PLANNER WITH ADAPTIVE COLLABORATIVE CONTROL TECHNOLOGIES (IMPACT)	
ORIGINATING ORGANISATION	AUTHOR
AFRL/711HPW	*Mark Draper*
DESCRIPTION:	
Agility in tactical decision making and mission management is a key attribute for enabling teams of heterogeneous Unmanned Vehicles (UxV) to successfully manage the "fog of war" with its inherently complex, ambiguous, and time-challenging conditions. This agility requires effective operator-autonomy teaming including the achievement of trusted collaboration and the flexible, high-level tasking required for team task sharing and decision superiority. A tri-service team within the US has conducted research focused on instantiating an "Intelligent Multi-UxV Planner with Adaptive Collaborative/Control Technologies" (IMPACT) by combining flexible play calling for task delegation, bi-directional human-autonomy interaction, advanced cooperative control algorithms, intelligent agent reasoning, and autonomic technologies to enable effective single operator Command and Control (C2) of cooperative multi-UxV missions. An IMPACT operator, with intelligent assistance, was able to dynamically task and manage a total of 12 UxV (four air, four ground, and four sea surface vehicles) in response to several unexpected events that arose during an ongoing base perimeter defence mission.	
UTILITY AND MILITARY BENEFIT	
Note that it is envisioned that IMPACT capabilities could support all these Use Cases by providing single operator tactical C2 of multiple UxVs in support of planned and new tasking. *Improved human effectiveness:* • *Dynamically managed workload while supervising multiple assets; faster and more accurate decisions.* *Increased automation performance/trustworthiness:* • *Enhanced performance via auto-monitoring of play execution with repair strategies for contingencies.* *Enhanced human-autonomy teaming:* • *Bi-directional comms, prioritised courses of action and task assignment, agile and flexible levels of control.* *Operational applications of anticipated utility:* • *C2, ISR, Agile Combat Support, Special operations, Resupply, etc.* *Operational benefits:* • *Force multiplication, reduced risk to humans, reduced manpower needs, optimised operator performance, increased collaboration, increased operational flexibility, agility and adaptability.*	

USE CASE 2: BASE PROTECTION			
USE CASE 2: SPECIFICS		**UTILITY**	**APPLICATION AND BENEFIT**
LOST EF	On the approach to the FOB, the EF is lost.	**N/A**	
COMINT (EF COORD)	COMINT is detected very close to the FOB. Indications are that this could lead to a coordinated attack on the FOB that may include a perimeter breach or a Vehicle-Borne IED (VBIED) strike.	**HIGH**	*Possible stimulus for agent-directed change in background behaviours towards a more "highly mobile" force protection level.*
VBIED SEARCH (TUAS/HMA) AND VBIED TRACK BY OUAS	TUAS and SUAS assets engaged on searching the base and the area around the base. Over SATCOM, OUAS track of a suspect vehicle heading towards the base is reported.	**HIGH**	*IMPACT can support the use of coordinated background behaviours simultaneously with multiple dedicated plays.*
MARITIME ISR DETECT	Teamed HMA and TUAS conducting maritime ISR detect a vessel operating outside of POL and is heading towards beach near FOB.	**MED**	*Track Play via IMPACT.*
VBIED TRACK/ HANDOVER ->SUAS	SUAS asset is tasked with picking up the suspect vehicle (VBIED).	**N/A**	
STOP VBIED	The suspect vehicle is stopped at the main gate (no detonation).	**N/A**	
EF PENETRATION OF FOB PERIMETER	Whilst there is activity at the main gate, the EF team manage to penetrate the Base fence perimeter.	**LOW**	*Possible detection by patrolling UxV's auto-target recognition.*
SEARCH/FIND EF TEAM NEAR BASE PERIMETER (TUAS/SUAS)	The EF penetration is reported and base ISR assets directed to find the EF team.	**HIGH**	*Area search play call with show of force.*
PID/FIX	Upon finding the EF team, they are positively identified by SUAS.	**N/A**	

USE CASE 2: BASE PROTECTION					
USE CASE 2: SPECIFICS			**UTILITY**	**APPLICATION AND BENEFIT**	
SEND FOOT PATROL AND CAPTURE	SUAS to provide overwatch of friendly force foot patrol sent in to capture EF.		**MED**	*Overwatch play call, single or multi-ship.*	
EF PICKUP BOAT (TUAS) – STRIKE / SHOW OF FORCE	The vessel being tracked by the HMA/TUAS team is identified as a potential pick up for the EF team. A show of force is requested to deter the vessel from nearing the coast.		**MED**	*Intercept play with show of force.*	
PRINCIPAL MISSION RISK					
If using IMPACT, need to guard against cyber threats that could spoof or deny C2 from this critical node. If not using IMPACT, possibility of reduced coordination/collaboration efficiency due to extra comms requirements associated with coordinating multiple UxV operators.					
PROBABILITY	EXTREMELY IMPROBABLE	IMPROBABLE	REMOTE	OCCASIONAL	FREQUENT
SEVERITY	CATASTROPHIC	SEVERE	MAJOR	MINOR	NEGLIGIBLE
COMMENTS					

Table 3-11: US-3: Bi-Directional Communication.

TECHNICAL ACTIVITY: US-3	
Bi-Directional Communication	
ORIGINATING ORGANISATION	AUTHOR
NASA	*Jay Shively*
DESCRIPTION:	
UTILITY AND MILITARY BENEFIT	

USE CASE 2: BASE PROTECTION			
USE CASE 2: SPECIFICS		**UTILITY**	**APPLICATION AND BENEFIT**
LOST EF	On the approach to the FOB, the EF is lost.	**N/A**	
COMINT (EF COORD)	COMINT is detected very close to the FOB. Indications are that this could lead to a coordinated attack on the FOB that may include a perimeter breach or a Vehicle-Borne IED (VBIED) strike.	**N/A**	
VBIED SEARCH (TUAS/HMA) AND VBIED TRACK BY OUAS	TUAS and SUAS assets engaged on searching the base and the area around the base. Over SATCOM, OUAS track of a suspect vehicle heading towards the base is reported.	**MED**	
MARITIME ISR DETECT	Teamed HMA and TUAS conducting maritime ISR detect a vessel operating outside of POL and is heading towards beach near FOB.	**MED**	

USE CASE 2: BASE PROTECTION			
USE CASE 2: SPECIFICS		**UTILITY**	**APPLICATION AND BENEFIT**
VBIED TRACK/ HANDOVER ->SUAS	SUAS asset is tasked with picking up the suspect vehicle (VBIED).	**LOW**	
STOP VBIED	The suspect vehicle is stopped at the main gate (no detonation).	**N/A**	
EF PENETRATION OF FOB PERIMETER	Whilst there is activity at the main gate, the EF team manage to penetrate the Base fence perimeter.	**N/A**	
SEARCH/FIND EF TEAM NEAR BASE PERIMETER (TUAS/SUAS)	The EF penetration is reported and base ISR assets directed to find the EF team.	**N/A**	
PID/FIX	Upon finding the EF team, they are positively identified by SUAS.	**HIGH**	
SEND FOOT PATROL AND CAPTURE	SUAS to provide overwatch of friendly force foot patrol sent in to capture EF.	**MED**	
EF PICKUP BOAT (TUAS) – STRIKE / SHOW OF FORCE	The vessel being tracked by the HMA/TUAS team is identified as a potential pick up for the EF team. A show of force is requested to deter the vessel from nearing the coast.	**MED**	

PRINCIPAL MISSION RISK					
Similar as above, but less dependence on automated systems.					
PROBABILITY	EXTREMELY IMPROBABLE	IMPROBABLE	REMOTE	**OCCASIONAL**	FREQUENT
SEVERITY	CATASTROPHIC	SEVERE	MAJOR	**MINOR**	NEGLIGIBLE
COMMENTS					

Table 3-12: US-4: Transparency.

TECHNICAL ACTIVITY: US-4 – HAT DESIGN PATTERN	
Transparency	
ORIGINATING ORGANISATION	AUTHOR
US Army Research Laboratory	Jessie Chen and Michael Barnes
DESCRIPTION:	
The goal of the Transparency Pattern is to provide a general human-machine interface design solution to support human-agent communications in order to achieve joint decision-making effectiveness. Drawing inspiration from Endsley's three levels of SA – perception, comprehension, and projection – the ***Situation Awareness-Based Agent Transparency*** *(SAT) model describes the information that agents need to convey about their decision-making process in order to facilitate the shared understanding required to perform effective human-agent teamwork. More specifically, the pattern describes the information requirement from the agent to support the human's awareness of the agent's:* *1) Current actions and plans;* *2) Reasoning process; and* *3) Outcome predictions and uncertainty.* *The Transparency Pattern based on the SAT model can be applied to a wide variety of human-machine interfaces, where the agent's reasoning information and projections of future outcomes (including uncertainty) are important to its/his/her team members (humans or machines).*	
UTILITY AND MILITARY BENEFIT	
The SAT model provides a useful framework for organising the information requirements related to agent transparency. More specifically, transparency on the part of the agent supports the human's: situation awareness regarding the agent, decision making and thus overall human-agent team performance, as well as trust calibration process (i.e., accepting the agent's plan when it is correct and rejecting it when it is incorrect). The benefits of the Transparency Pattern includes: improved human effectiveness (human-in-the-loop control and command authority), increased automation performance and trustworthiness (agents can be utilised optimally based on their capabilities due to their greater predictability and understandability to the humans), and enhanced human-autonomy teaming (communication, coordination, cooperation, collaboration, and adaptivity). The Transparency Pattern is anticipated to be particularly useful for C2-related applications and missions involving Intelligent Agents (IAs). The anticipated operational benefits include: optimised operator performance, reduced training requirements, improved contingency management, increased operational flexibility, agility and adaptability. Because of the complexity of the ISR mission, it could only be accomplished by increasing manpower or with IA assistance. However, the human must have situation awareness of the mission and of the IA in order to ensure mission success.	

USE CASE 2: BASE PROTECTION			
USE CASE 2: SPECIFICS		**UTILITY**	**APPLICATION AND BENEFIT**
LOST EF	On the approach to the FOB, the EF is lost.	**N/A**	
COMINT (EF COORD)	COMINT is detected very close to the FOB. Indications are that this could lead to a coordinated attack on the FOB that may include a perimeter breach or a Vehicle-Borne IED (VBIED) strike.	**N/A**	
VBIED SEARCH (TUAS/HMA) AND VBIED TRACK BY OUAS	TUAS and SUAS assets engaged on searching the base and the area around the base. Over SATCOM, OUAS track of a suspect vehicle heading towards the base is reported.	**HIGH**	*Assets indicating their 1) Current actions and plans; 2) Reasoning process; and 3) Outcome predictions and uncertainty.*
MARITIME ISR DETECT	Teamed HMA and TUAS conducting maritime ISR detect a vessel operating outside of POL and is heading towards beach near FOB.	**HIGH**	*TUAS indicating its 1) Current actions and plans; 2) Reasoning process; and 3) Outcome predictions and uncertainty.*
VBIED TRACK/ HANDOVER ->SUAS	SUAS asset is tasked with picking up the suspect vehicle (VBIED).	**HIGH**	*SUAS indicating its 1) Current actions and plans; 2) Reasoning process; and 3) Outcome predictions and uncertainty.*
STOP VBIED	The suspect vehicle is stopped at the main gate (no detonation).	**N/A**	
EF PENETRATION OF FOB PERIMETER	Whilst there is activity at the main gate, the EF team manage to penetrate the Base fence perimeter.	**N/A**	
SEARCH/FIND EF TEAM NEAR BASE PERIMETER (TUAS/SUAS)	The EF penetration is reported and base ISR assets directed to find the EF team.	**MED**	*Assets indicating their 1) Current actions and plans; 2) Reasoning process; and 3) Outcome predictions and uncertainty.*

USE CASE 2: BASE PROTECTION			
USE CASE 2: SPECIFICS		**UTILITY**	**APPLICATION AND BENEFIT**
PID/FIX	Upon finding the EF team, they are positively identified by SUAS.	**HIGH**	*SUAS indicating its 1) Current actions and plans; 2) Reasoning process; and 3) Outcome predictions and uncertainty.*
SEND FOOT PATROL AND CAPTURE	SUAS to provide overwatch of friendly force foot patrol sent in to capture EF.	**HIGH**	*SUAS indicating its 1) Current actions and plans; 2) Reasoning process; and 3) Outcome predictions and uncertainty.*
EF PICKUP BOAT (TUAS) – STRIKE / SHOW OF FORCE	The vessel being tracked by the HMA/TUAS team is identified as a potential pick up for the EF team. A show of force is requested to deter the vessel from nearing the coast.	**HIGH**	*Assets indicating their 1) Current actions and plans; 2) Reasoning process; and 3) Outcome predictions and uncertainty.*

PRINCIPAL MISSION RISK
Mission risks of not using the Transparency Pattern include: degraded human operator's situation awareness of the agents' (ISR assets and TUASs) current actions and plans, reasoning process, projected outcomes and uncertainty; suboptimal decision making on the part of the human operator due to his/her understanding of the agents (e.g., disuse or misuse of the agent); increased operator workload due to the needs for the human to understand the agents' behaviours.

PROBABILITY	EXTREMELY IMPROBABLE	IMPROBABLE	REMOTE	OCCASIONAL	**FREQUENT**
SEVERITY	CATASTROPHIC	**SEVERE**	MAJOR	MINOR	NEGLIGIBLE

COMMENTS

OTHER MISSION RISKS

REFERENCES [21], [22].

3.6 USE CASE THREE – TIC: APPLICATION AND BENEFIT

Table 3-13 is a summary of the utility (high, medium and low) for each TA or HAT Pattern. The following tables are a detailed input from each nation for Use Case Three:

UK-1: HAT Collaborative Verification and Validation – Adaptable Autonomy and Policy Management: Development, Test and Evaluation (Table 3-14);

US-1: Task Management and Plan Monitoring (Table 3-15);

US-2: Intelligent Multi-Unmanned Vehicle Planner with Adaptive Collaborative Control Technologies (IMPACT) (Table 3-16);

US-3: Bi-Directional Communication (Table 3-17); and

US-4: Transparency (Table 3-18).

Table 3-13: A Summary of the Utility (High, Medium and Low) for Each TA or HAT Pattern.

USE CASE 3: TROOPS IN CONTACT (TIC)						
USE CASE SPECIFICS		**UK-1**	**US-1**	**US-2**	**US-3**	**US-4**
VBIED UNSUCCESSFUL	VBIED attack at main FOB gate has failed.	**N/A**	**MED**	**N/A**	**N/A**	**N/A**
EF REPLAN IED EMPLACEMENT OFF BASE	EF Team replan their attack around the base.	**HIGH**	**HIGH**	**N/A**	**N/A**	**N/A**
EF MATERIALS FROM SEA	Suspect vessel close to shore monitored by maritime ISR TUAS. Vessel reaches shore and people disembark.	**HIGH**	**HIGH**	**MED**	**LOW**	**MED**
HANDED TO VEHICLE	EF Vehicle on beach. EF personnel are moving packages to the vehicle from the vessel. Vehicle moves off.	**HIGH**	**HIGH**	**N/A**	**LOW**	**N/A**
VEHICLE DROPS 1ST TEAM AND MOVES OFF	EF Vehicle moves to a location close to the FOB and deploys a small EF Team (team 1). The vehicle then moves off. EF Team begin process of planting IEDs.	**HIGH**	**HIGH**	**N/A**	**N/A**	**N/A**
VEHICLE MOVES TO SECOND POTENTIAL IED EMPLACEMENT	EF Vehicle moves to a second location. Driver stays with vehicle.	**HIGH**	**HIGH**	**N/A**	**N/A**	**N/A**

USE CASE 3: TROOPS IN CONTACT (TIC)						
USE CASE SPECIFICS		UK-1	US-1	US-2	US-3	US-4
STRIKE VEHICLE (EF TEAM 2)	Strike mission is called against the EF vehicle. Strike assets makes use of imagery from available UAS to PID target and undertake BDA.	**HIGH**	**HIGH**	**HIGH**	**N/A**	**MED**
FF(GND) INTERCEPT EF TEAM 1	Friendly ground forces are tasked to intercept the first EF team.	**HIGH**	**HIGH**	**MED**	**N/A**	**N/A**
TIC	Friendly forces engage the EF team and take casualties. Embedded JTAC requests CASEVAC.	**HIGH**	**HIGH**	**N/A**	**N/A**	**N/A**
CASEVAC	Support Helicopter from MOB undertakes CASEVAC mission utilising imagery from available UAS to clear approach and landing zone.	**HIGH**	**HIGH**	**N/A**	**N/A**	**MED**

Table 3-14: UK-1: HAT Collaborative Verification and Validation – Adaptable Autonomy and Policy Management: Development, Test and Evaluation.

TECHNICAL ACTIVITY: UK-1	
HAT Collaborative Verification and Validation *Adaptable Autonomy and Policy Management: Development, Test and Evaluation*	
ORIGINATING ORGANISATION	AUTHOR
QinetiQ	M Thomas
DESCRIPTION:	

Adaptable Autonomy *with automated* ***Policy Management*** *functionality has been developed and tested within the UK Live, Virtual and Constructive environment to evaluate core mission enabling technologies underpinning the exploitation of* ***Human-Autonomy Teaming*** *with intelligent unmanned systems, including:*
• *Situation Assessment Support System (SASS) used to monitor external and internal environments, assessing consequences and identifying appropriate courses of action.*
• *Policy Management (PolMan) automation maintains a database of applicable policies which serves to ensure policy compliance, identifies policy violations and provides mitigations.*
  • *Conflict resolution; and*
  • *Negotiation.*
• *Development and Management of Autonomy Behaviours.*
  • *Multi-Platform Task Scheduling;*
  • *SAR Tactics Planner;*
  • *Intelligent Routing and Hold Pattern Tactics; and*
  • *Multiple Search Tactics.*
• *Manned-Unmanned Teaming (MUMT).*
  • *Level of Interoperability control; and*
  • *Handover.*	

UTILITY AND MILITARY BENEFIT	
• *AA, using SASS and Policy Management, alerts operators to potential violations and conflicts in applicable policies in the planning and execution of missions.* • *Conflict Resolution mitigation includes recommendations for automated negotiations with relevant agencies.* • *Task scheduling and planning of multi-platform heterogeneous ISR assets. PolMan ensures plan deconfliction for multiple platforms and respective airspace allocations.* • *Policy Management ensures increased automation performance and trustworthiness through correct and timely usage of complex autonomy behaviours.* • *Increase decision speed (agility) and decision quality (adaptability) in multi-asset control and manned-unmanned teaming.*	

USE CASE 3: TROOPS IN CONTACT (TIC)			
USE CASE SPECIFICS		**UTILITY**	**APPLICATION AND BENEFIT**
VBIED UNSUCCESSFUL	VBIED attack at main FOB gate has failed.	**N/A**	*Pre-amble and set up use case.*
EF REPLAN IED EMPLACEMENT OFF BASE	EF Team replan their attack around the base.	**HIGH**	*SASS, using PolMan, alerts operators to potential airspace policy conflicts by the SUAS whilst on task.*
EF MATERIALS FROM SEA	Suspect vessel close to shore monitored by maritime ISR TUAS. Vessel reaches shore and people disembark.	**HIGH**	*SASS, PolMan and MUMT functionality supports operator SA in undertaking complex multi- platform coordination and control as well as managing potential airspace conflicts and negotiations.*
HANDED TO VEHICLE	EF Vehicle on beach. EF personnel are moving packages to the vehicle from the vessel. Vehicle moves off.	**HIGH**	*Task scheduling and PolMan to maximise UAS assets and direct application of correct autonomy behaviours whilst maintaining airspace deconfliction between multiple assets.*
VEHICLE DROPS 1ST TEAM AND MOVES OFF	EF Vehicle moves to a location close to the FOB and deploys a small EF Team (team 1). The vehicle then moves off. EF Team begin process of planting IEDs.	**HIGH**	*Task scheduling and PolMan to maximise UAS assets and direct application of correct autonomy behaviours whilst maintaining airspace deconfliction between multiple assets undertaking different tasks.*
VEHICLE MOVES TO SECOND POTENTIAL IED EMPLACEMENT	EF Vehicle moves to a second location. Driver stays with vehicle.	**HIGH**	*SASS, using PolMan, alerts operators to potential airspace policy conflicts by the SUAS whilst on task.*
STRIKE VEHICLE (EF TEAM 2)	Strike mission is called against the EF vehicle. Strike assets makes use of imagery from available UAS to PID target and undertake BDA.	**HIGH**	*SASS, using PolMan and Negotiations, to support rescheduling of assets and airspace deconfliction in order to support Strike operation.*
FF(GND) INTERCEPT EF TEAM 1	Friendly ground forces are tasked to intercept the first EF team.	**HIGH**	*SASS, using PolMan, alerts operators to potential airspace policy conflicts by the SUAS whilst on task.*

USE CASE 3: TROOPS IN CONTACT (TIC)			
USE CASE SPECIFICS		**UTILITY**	**APPLICATION AND BENEFIT**
TIC	Friendly forces engage the EF team and take casualties. Embedded JTAC requests CASEVAC.	**HIGH**	*SASS, using PolMan and Negotiations, to support rescheduling of assets and airspace deconfliction in order to support CASEVAC operation.*
CASEVAC	Support Helicopter from MOB undertakes CASEVAC mission utilising imagery from available UAS to clear approach and landing zone.	**HIGH**	*SASS, using PolMan, alerts operators to potential dynamic airspace policy conflicts by the UAS on task in vicinity of CASEVAC.*

PRINCIPAL MISSION RISK

Without SASS, PolMan and automated negotiations, there is a dependency on the unreliable human supervisory role to be aware for all task and dynamic airspace conflicts, requiring manual intervention to manage airspace access and restrictions, and platform deconflictions.

Could be deemed to be a Safety Critical issue (severe) if there is a risk of SUAS collision in confined airspace zones (SUAS Keep in Zones ~ 500 m).

PROBABILITY	EXTREMELY IMPROBABLE	IMPROBABLE	REMOTE	**OCCASIONAL**	FREQUENT
SEVERITY	CATASTROPHIC	**SEVERE**	MAJOR	MINOR	NEGLIGIBLE

COMMENTS

Without SASS, PolMan and automated negotiations, there is a dependency on the unreliable human supervisory role to be aware for all task and dynamic airspace conflicts, requiring manual intervention to manage airspace access and restrictions, and platform deconflictions.

Could be deemed to be a Safety Critical issue (severe) if there is a risk of SUAS collision with manned aircraft in confined airspace zones (SUAS Keep in Zones ~ 500 m and overlapping CASEVAC Landing Zone).

OTHER MISSION RISKS

Not completing tasks effectively – suboptimal search plans.

Loss of automation/autonomy operator trust.

Adversely effecting other task lines (platform operators).

REFERENCES [18], [19], [20].

ADDITIONAL INFORMATION

OTHER RELEVANT MILITARY APPLICATIONS AND USE CASES

All applications of Decision Support, Automation and Autonomy, in air, land and maritime domain which also includes both unmanned and manned systems (such as traditional 'associate' programmes, US PA, US RPA/CDAS, UK MMA, UK CogPit [23], UK FOAEW/MASC [24], UK MATDSS TDP [24], Fr Copilot Electronique [24], [25], Gr CAMA [26], [24]).

Table 3-15: US-1: Task Management and Plan Monitoring.

TECHNICAL ACTIVITY: US-1			
Task Management and Plan Monitoring			
ORIGINATING ORGANISATION	AUTHOR		
Space and Naval Warfare Systems Center Pacific	*Doug Lange*		
DESCRIPTION:			
The task manager capable of determining user tasks, dividing tasks into a hierarchy, presenting tasks to the user, and providing a mechanism to execute an action for each task. It is intended to allow a human operator to work in a complex environment and provide for some task load balancing between the human and autonomous assistants. *Plan monitor evaluates the progress of the execution of plans and utilises strategies for correcting problems. These can include fully autonomous strategies, or those that involve the human operator.*			
UTILITY AND MILITARY BENEFIT			
Complex environments with large numbers of plans being executed simultaneously put a burden on human operators. TM and PM team with the human to allow for better command and control of the available forces and over the tactical situation.			
USE CASE 3: TROOPS IN CONTACT (TIC)			
USE CASE 3 SPECIFICS		**UTILITY**	**APPLICATION AND BENEFIT**
VBIED UNSUCCESSFUL	VBIED attack at main FOB gate has failed.	**MED**	
EF REPLAN IED EMPLACEMENT OFF BASE	EF Team replan their attack around the base.	**HIGH**	
EF MATERIALS FROM SEA	Suspect vessel close to shore monitored by maritime ISR TUAS. Vessel reaches shore and people disembark.	**HIGH**	
HANDED TO VEHICLE	EF Vehicle on beach. EF personnel are moving packages to the vehicle from the vessel. Vehicle moves off.	**HIGH**	
VEHICLE DROPS 1ST TEAM AND MOVES OFF	EF Vehicle moves to a location close to the FOB and deploys a small EF Team (team 1). The vehicle then moves off. EF Team begin process of planting IEDs.	**HIGH**	
VEHICLE MOVES TO SECOND POTENTIAL IED EMPLACEMENT	EF Vehicle moves to a second location. Driver stays with vehicle.	**HIGH**	

STRIKE VEHICLE (EF TEAM 2)	Strike mission is called against the EF vehicle. Strike assets makes use of imagery from available UAS to PID target and undertake BDA.	**HIGH**	
FF(GND) INTERCEPT EF TEAM 1	Friendly ground forces are tasked to intercept the first EF team.	**HIGH**	
TIC	Friendly forces engage the EF team and take casualties. Embedded JTAC requests CASEVAC.	**HIGH**	
CASEVAC	Support Helicopter from MOB undertakes CASEVAC mission utilising imagery from available UAS to clear approach and landing zone.	**HIGH**	

PRINCIPAL MISSION RISK					
PROBABILITY	EXTREMELY IMPROBABLE	IMPROBABLE	REMOTE	OCCASIONAL	**FREQUENT**
SEVERITY	CATASTROPHIC	**SEVERE**	MAJOR	MINOR	NEGLIGIBLE

COMMENTS
TM and PM become important in high complexity environments. Each of the use cases above provide little challenge on their own. It is the combination of all of them occurring within a scenario that provides the requisite complexity. Operators found this level of scenario difficult without TM and PM, and yet this is not an overly complex scenario. Therefore, in scenarios at this level of complexity or higher there are frequently situations where these capabilities are important and the severity of not having them can be severe.

OTHER MISSION RISKS

Table 3-16: US-2: Intelligent Multi-Unmanned Vehicle Planner with Adaptive Collaborative Control Technologies (IMPACT).

TECHNICAL ACTIVITY: US-2	
INTELLIGENT MULTI-UNMANNED VEHICLE PLANNER WITH ADAPTIVE COLLABORATIVE CONTROL TECHNOLOGIES (IMPACT)	
ORIGINATING ORGANISATION	AUTHOR
AFRL/711HPW	*Mark Draper*
DESCRIPTION:	
Agility in tactical decision making and mission management is a key attribute for enabling teams of heterogeneous Unmanned Vehicles (UxV) to successfully manage the "fog of war" with its inherently complex, ambiguous, and time-challenging conditions. This agility requires effective operator-autonomy teaming including the achievement of trusted collaboration and the flexible, high-level tasking required for team task sharing and decision superiority. A tri-service team within the US has conducted research focused on instantiating an "Intelligent Multi-UxV Planner with Adaptive Collaborative/Control Technologies" (IMPACT) by combining flexible play calling for task delegation, bi-directional human-autonomy interaction, advanced cooperative control algorithms, intelligent agent reasoning, and autonomic technologies to enable effective single operator Command and Control (C2) of cooperative multi-UxV missions. An IMPACT operator, with intelligent assistance, was able to dynamically task and manage a total of 12 UxV (four air, four ground, and four sea surface vehicles) in response to several unexpected events that arose during an ongoing base perimeter defence mission.	
UTILITY AND MILITARY BENEFIT	
Note that it is envisioned that IMPACT capabilities could support all these Use Cases by providing single operator tactical C2 of multiple UxVs in support of planned and new tasking. *Improved human effectiveness:* • *Dynamically managed workload while supervising multiple assets; faster and more accurate decisions.* *Increased automation performance/trustworthiness:* • *Enhanced performance via auto-monitoring of play execution with repair strategies for contingencies.* *Enhanced human-autonomy teaming:* • *Bi-directional comms, prioritised courses of action and task assignment, agile and flexible levels of control.* *Operational applications of anticipated utility:* • *C2, ISR, Agile Combat Support, Special operations, Resupply, etc.* *Operational benefits:* • *Force multiplication, reduced risk to humans, reduced manpower needs, optimised operator performance, increased collaboration, increased operational flexibility, agility and adaptability.*	

USE CASE 3: TROOPS IN CONTACT (TIC)			
USE CASE 3 SPECIFICS		**UTILITY**	**APPLICATION AND BENEFIT**
VBIED UNSUCCESSFUL	VBIED attack at main FOB gate has failed.	**N/A**	
EF REPLAN IED EMPLACEMENT OFF BASE	EF Team replan their attack around the base.	**N/A**	
EF MATERIALS FROM SEA	Suspect vessel close to shore monitored by maritime ISR TUAS. Vessel reaches shore and people disembark.	**MED**	*IMPACT provides C2 oversight and coordination with manned assets.*
HANDED TO VEHICLE	EF Vehicle on beach. EF personnel are moving packages to the vehicle from the vessel. Vehicle moves off.	**N/A**	
VEHICLE DROPS 1ST TEAM AND MOVES OFF	EF Vehicle moves to a location close to the FOB and deploys a small EF Team (team 1). The vehicle then moves off. EF Team begin process of planting IEDs.	**N/A**	
VEHICLE MOVES TO SECOND POTENTIAL IED EMPLACEMENT	EF Vehicle moves to a second location. Driver stays with vehicle.	**N/A**	
STRIKE VEHICLE (EF TEAM 2)	Strike mission is called against the EF vehicle. Strike assets makes use of imagery from available UAS to PID target and undertake BDA.	**HIGH**	*IMPACT supports strike with coordinated ISR and BDA plays.*
FF(GND) INTERCEPT EF TEAM 1	Friendly ground forces are tasked to intercept the first EF team.	**MED**	*IMPACT provides convoy tracking and overwatch support plays to ground forces.*
TIC	Friendly forces engage the EF team and take casualties. Embedded JTAC requests CASEVAC.	**N/A**	
CASEVAC	Support Helicopter from MOB undertakes CASEVAC mission utilising imagery from available UAS to clear approach and landing zone.	**N/A**	

PRINCIPAL MISSION RISK					
Same risks as before, as IMPACT plays the same supporting role as tactical C2 node of multiple UxVs in area.					
PROBABILITY	EXTREMELY IMPROBABLE	IMPROBABLE	REMOTE	OCCASIONAL	FREQUENT
SEVERITY	CATASTROPHIC	SEVERE	MAJOR	MINOR	NEGLIGIBLE
COMMENTS					
OTHER MISSION RISKS					
ADDITIONAL INFORMATION					
OTHER RELEVANT MILITARY APPLICATIONS AND USE CASES					
IMPACT associated tools and technologies can potentially apply to many different military mission sets. Examples include manned-unmanned teaming, aerial port operations, and cyber operations.					

Table 3-17: US-3: Bi-Directional Communication.

TECHNICAL ACTIVITY: US-3			
Bi-Directional Communication			
ORIGINATING ORGANISATION	AUTHOR		
NASA	*Jay Shively*		
DESCRIPTION:			
UTILITY AND MILITARY BENEFIT			
USE CASE 3: TROOPS IN CONTACT (TIC)			
USE CASE SPECIFICS		**UTILITY**	**APPLICATION AND BENEFIT**
VBIED UNSUCCESSFUL	VBIED attack at main FOB gate has failed.	**N/A**	
EF REPLAN IED EMPLACEMENT OFF BASE	EF Team replan their attack around the base.	**N/A**	
EF MATERIALS FROM SEA	Suspect vessel close to shore monitored by maritime ISR TUAS. Vessel reaches shore and people disembark.	**LOW**	
HANDED TO VEHICLE	EF Vehicle on beach. EF personnel are moving packages to the vehicle from the vessel. Vehicle moves off.	**LOW**	
VEHICLE DROPS 1ST TEAM AND MOVES OFF	EF Vehicle moves to a location close to the FOB and deploys a small EF Team (team 1). The vehicle then moves off. EF Team begin process of planting IEDs.	**N/A**	

VEHICLE MOVES TO SECOND POTENTIAL IED EMPLACEMENT	EF Vehicle moves to a second location. Driver stays with vehicle.	**N/A**	
STRIKE VEHICLE (EF TEAM 2)	Strike mission is called against the EF vehicle. Strike assets makes use of imagery from available UAS to PID target and undertake BDA.	**N/A**	
FF(GND) INTERCEPT EF TEAM 1	Friendly ground forces are tasked to intercept the first EF team.	**N/A**	
TIC	Friendly forces engage the EF team and take casualties. Embedded JTAC requests CASEVAC.	**N/A**	
CASEVAC	Support Helicopter from MOB undertakes CASEVAC mission utilising imagery from available UAS to clear approach and landing zone	**N/A**	

PRINCIPAL MISSION RISK					
N/A					
PROBABILITY	EXTREMELY IMPROBABLE	IMPROBABLE	REMOTE	OCCASIONAL	FREQUENT
SEVERITY	CATASTROPHIC	SEVERE	MAJOR	MINOR	NEGLIGIBLE

COMMENTS

OTHER MISSION RISKS

Table 3-18: US-4: Transparency.

TECHNICAL ACTIVITY: US-4 – HAT DESIGN PATTERN	
Transparency	
ORIGINATING ORGANISATION	AUTHOR
US Army Research Laboratory	Jessie Chen and Michael Barnes
DESCRIPTION:	
*The goal of the Transparency Pattern is to provide a general human-machine interface design solution to support human-agent communications in order to achieve joint decision-making effectiveness. Drawing inspiration from Endsley's three levels of SA – perception, comprehension, and projection – the **Situation Awareness-Based Agent Transparency** (SAT) model describes the information that agents need to convey about their decision-making process in order to facilitate the shared understanding required to perform effective human-agent teamwork. More specifically, the pattern describes the information requirement from the agent to support the human's awareness of the agent's:* *1) Current actions and plans;* *2) Reasoning process; and* *3) Outcome predictions and uncertainty.* *The Transparency Pattern based on the SAT model can be applied to a wide variety of human-machine interfaces, where the agent's reasoning information and projections of future outcomes (including uncertainty) are important to its/his/her team members (humans or machines).*	
UTILITY AND MILITARY BENEFIT	
The SAT model provides a useful framework for organising the information requirements related to agent transparency. More specifically, transparency on the part of the agent supports the human's: situation awareness regarding the agent, decision making and thus overall human-agent team performance, as well as trust calibration process (i.e., accepting the agent's plan when it is correct and rejecting it when it is incorrect). The benefits of the Transparency Pattern includes: improved human effectiveness (human-in-the-loop control and command authority), increased automation performance and trustworthiness (agents can be utilised optimally based on their capabilities due to their greater predictability and understandability to the humans), and enhanced human-autonomy teaming (communication, coordination, cooperation, collaboration, and adaptivity). The Transparency Pattern is anticipated to be particularly useful for C2-related applications and missions involving Intelligent Agents (IAs). The anticipated operational benefits include: optimised operator performance, reduced training requirements, improved contingency management, increased operational flexibility, agility and adaptability. Because of the complexity of the ISR mission, it could only be accomplished by increasing manpower or with IA assistance. However, the human must have situation awareness of the mission and of the IA in order to ensure mission success.	

USE CASE 3: TROOPS IN CONTACT (TIC)			
USE CASE SPECIFICS		**UTILITY**	**APPLICATION AND BENEFIT**
VBIED UNSUCCESSFUL	VBIED attack at main FOB gate has failed.	**N/A**	

USE CASE 3: TROOPS IN CONTACT (TIC)			
USE CASE SPECIFICS		**UTILITY**	**APPLICATION AND BENEFIT**
EF REPLAN IED EMPLACEMENT OFF BASE	EF Team replan their attack around the base.	**N/A**	
EF MATERIALS FROM SEA	Suspect vessel close to shore monitored by maritime ISR TUAS. Vessel reaches shore and people disembark.	**MED**	*TUAS indicating its 1) Current actions and plans; 2) Reasoning process; and 3) Outcome predictions and uncertainty.*
HANDED TO VEHICLE	EF Vehicle on beach. EF personnel are moving packages to the vehicle from the vessel. Vehicle moves off.	**N/A**	
VEHICLE DROPS 1ST TEAM AND MOVES OFF	EF Vehicle moves to a location close to the FOB and deploys a small EF Team (team 1). The vehicle then moves off. EF Team begin process of planting IEDs.	**N/A**	
VEHICLE MOVES TO SECOND POTENTIAL IED EMPLACEMENT	EF Vehicle moves to a second location. Driver stays with vehicle.	**N/A**	
STRIKE VEHICLE (EF TEAM 2)	Strike mission is called against the EF vehicle. Strike assets makes use of imagery from available UAS to PID target and undertake BDA.	**MED**	*UAS indicating its 1) Current actions and plans; 2) Reasoning process; and 3) Outcome predictions and uncertainty.*
FF(GND) INTERCEPT EF TEAM 1	Friendly ground forces are tasked to intercept the first EF team.	**N/A**	
TIC	Friendly forces engage the EF team and take casualties. Embedded JTAC requests CASEVAC.	**N/A**	
CASEVAC	Support Helicopter from MOB undertakes CASEVAC mission utilising imagery from available UAS to clear approach and landing zone.	**MED**	*UAS indicating its 1) Current actions and plans; 2) Reasoning process; and 3) Outcome predictions and uncertainty.*

PRINCIPAL MISSION RISK					
Mission risks of not using the Transparency Pattern include: degraded human operator's situation awareness of the agents' (ISR assets and TUASs) current actions and plans, reasoning process, projected outcomes and uncertainty; suboptimal decision making on the part of the human operator due to his/her understanding of the agents (e.g., disuse or misuse of the agent); increased operator workload due to the needs for the human to understand the agents' behaviours.					
PROBABILITY	EXTREMELY IMPROBABLE	IMPROBABLE	REMOTE	**OCCASIONAL**	FREQUENT
SEVERITY	CATASTROPHIC	SEVERE	**MAJOR**	MINOR	NEGLIGIBLE
COMMENTS					
OTHER MISSION RISKS					
REFERENCES [21], [22].					
ADDITIONAL INFORMATION					
OTHER RELEVANT MILITARY APPLICATIONS AND USE CASES					
The Transparency Pattern (SAT model) has been used in designing a Warfighter-Machine Interface (WMI) of a simulated small ground robot working in a dismounted infantry environment. The WMI incorporated an "at-a-glance" transparency module based on the SAT model to convey the robot's current actions, reasoning process (top "motivator"), and projected outcomes based on current actions/plans and uncertainty. This effort was supported by the Autonomous Squad Member project under the US Office of Secretary of Defense's Autonomy Research Pilot Initiative [21].					

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Chapter 4 – HAT DESIGN PATTERNS

Douglas S. Lange
Naval Information Warfare Center, Pacific
UNITED STATES

Christopher Miller
Smart Information Flow Technologies
UNITED STATES

Axel Schulte and Diana Donath
Universität der Bundeswehr München, Institute of Flight Systems (IFS)
GERMANY

R. Jay Shively
NASA Ames Research Center
UNITED STATES

Gilles Coppin
IMT Atlantique
FRANCE

Lavinia Burski
QinetiQ
UNITED KINGDOM

Robert S. Gutzwiller, Sarah H. Espinosa, Caitlin Kenny, and Douglas S. Lange
Space and Naval Warfare Systems Center, Pacific
UNITED STATES

Mark A. Neerincx
TNO, Perceptual and Cognitive Systems
THE NETHERLANDS

Jessie Y.C. Chen, Michael J. Barnes
US Army Research Laboratory
UNITED STATES

4.1 DESIGN PATTERNS FOR HUMAN-AUTONOMY TEAMING

4.1.1 Overview and Scope

Christopher Alexander proposed that every building and town is composed of patterns [1]. The patterns are a result of forces and processes that combine such that towns or buildings develop in particular ways. By developing a language of these patterns, Alexander et al. were able to describe the forces that produced patterns as well as the consequences of those patterns [2]. Pattern descriptions also specified their relationships to other patterns so that one could create a network of patterns to describe a project. Finally, Alexander et al. set out processes by which the patterns could be used. They envisioned the descriptions of forces and consequences as useful in making arguments to decision-making bodies. They also described how one could specify a project from top-down using patterns to make decisions about the ultimate design.

Design patterns and pattern languages became a popular tool for software engineering in the 1990s. This is usually traced to Gamma et al. in 1995 [2]. That patterns described a repeated problem and the core of a solution to that problem class is their fundamental value. Gamma et al. tried to be more explicit than Alexander concerning the components of a pattern. Four critical elements were listed: the pattern name, the description of the problem, the description of the solution, and the consequences. A more detailed template was created, and their book [2], like the second volume of Alexander's work [2] provided a library of some discovered patterns, each describing a suitable problem space, the solution template, positive and negative consequences, and giving implementation advice. The popularity of software patterns led to further efforts to catalog patterns for software analysis [4] and design [5], and data models [5]. Discussions of negative patterns often found in systems or organizations were described as anti-patterns [6] with discussions of how to correct the problems. Conferences were held to capture the experience

of practitioners in program design as a counterweight to scientific activities that focused on new approaches [7]. Juziuk [8] is the first author to provide a comprehensive listing and overview of efforts to document patterns in multi-agent systems. This gets us closer to what we need for Human-Autonomy Teaming (HAT), in that cognitive agents and their relationships to each other are considered.

Ultimately, a pattern literature for HAT will accomplish the same goals that Alexander initially set out in the domain of architecture and land-use. Patterns serve to communicate generalized solutions to problems faced by engineers. Alexander believed that one could re-use patterns by looking through a catalog of patterns, identify the key features and forces of a project, and select the appropriate starting points. Then using the linkages provided among the patterns in his catalog one could bring in other appropriate patterns until one had a description in the form of a language of patterns. Our forces will include human performance issues, limitations of autonomy, communication issues, and many other critical factors. If our patterns can describe forces, features, consequences, and linkages to other patterns, this may be possible within this domain.

In the field of human factors and ergonomics, the description of design patterns also became fashionable recently. Borchers [9] is one of the first who described the linkage between human-computer interaction and design patterns. Kruschitz and Hitz [10] also provide a good overview. Kahn et al. [11] looked at design patterns for sociality in human-robot interaction.

Sheridan's well-known Levels of Automation (LoA) scale (e.g., Ref. [12]) is one of the early design patterns in human-automation interaction. System designers very successfully use this scale or one of its derivatives (e.g., Ref. [13], [14]) in many different application fields, sometimes even without knowing. In that sense, we see these kinds of Management-by-Consent-based / Management-by-Exception-based LoA scales as a collection of often-found design patterns. They apply for supervisory control relationships [12] between human and machine. In this use case, LoA scales provide an excellent source for deciding how to design the interaction for certain specific functions. Scales of levels of autonomy (e.g., Ref. [15], [16]) refer more to design options for the scope of a full system. Their focus is predominantly on the description of the independence of the system from human intervention.

HFM-247 chose to use patterns to describe solutions found or proposed within our technical activities. The goal is to begin to create a NATO pattern catalog for HAT that can be built upon, allowing those within the alliance to share information more readily about our work.

4.2 SYSTEMS-LEVEL DESIGN PATTERNS APPROACH FOR HAT

4.2.1 Overview and Scope

The aim of this section (cf. Ref. [1]) is to provide a common, easy to use nomenclature to describe highly automated human-machine systems in the realm of vehicle guidance and foster the identification of established design patterns for human-autonomy teaming. With this effort, we intend to facilitate the discussion and exchange of approaches to the integration of humans with cognitive agents among researchers and system designers. By use of this nomenclature, we identify most important top-level design patterns, such as delegation and associate systems, as well as hybrid structures of humans working with cognitive agents.

4.2.2 Introduction

Today, higher cognitive functions (e.g., perception, planning, and decision making) that are traditionally exclusively owned by the human, are becoming an integral part of automated functions. In the last one or two decades the term "autonomous system" has widely been used to describe complex automated systems working

largely independent from a human operator. However, the more capable the automation has become, the more essential the challenging issue of human-system functional allocation and integration has turned out to be [18]. We share the concern of Bradshaw et al. [19] that an undifferentiated use of the term "autonomy" and the proliferation of automation can lead to unfruitful discussions and oddly defined development programs. We see the need for a conceptual framework unifying the nomenclature and description of systems in which human beings interact with complex automation.

Therefore, we attempt to identify and formally describe common grounds among researchers in this field. Despite our concerns, we want to adhere to the term ***Human-Autonomy Teaming (HAT)*** to describe systems in which humans work with highly automated agents. Where those agents carry attributes like "autonomous" or "intelligent", we will assign the unified term ***Cognitive Agent*** in this nomenclature. We establish a procedure and a common language to describe concepts of HAT. Our goal is to contribute to a more objective debate, to facilitate the effective communication between researchers, and to provide guidance to practitioners.

Our approach, in general, is twofold. Firstly, we suggest a ***common symbolic and graphical language***, as well as a procedure to follow to describe systems, system requirements, and top-level system designs. Both have a stronger focus on human-automation work share and integration aspects than traditional systems engineering practices and tools (e.g., Unified Modelling Language, UML). We borrow the notion of ***design patterns*** from the domain of systems and software engineering and adapt it for use in human factors engineering of highly automated dynamic systems. Secondly, we encourage the analysis of current HAT research and development approaches in order to ***identify solutions and best practices*** from empirical studies. This section shall also provide advice for designers of HAT systems how to approach the design process in a strictly top-down manner.

4.2.2.1 Design Patterns in Engineering

Christopher Alexander proposed that every building and town is composed of patterns [1]. The patterns are a result of forces and processes that combine such that towns or buildings develop in particular ways. By developing a language of these patterns, Alexander et al. were able to describe the forces that produced patterns as well as the consequences of those patterns [2]. Pattern descriptions also specified their relationships to other patterns so that one could create a network of patterns to describe a project. Finally, Alexander et al. set out processes by which the patterns could be used. They envisioned the descriptions of forces and consequences as useful in making arguments to decision-making bodies. They also described how one could ***specify a project from top-down using patterns*** to make decisions about the ultimate design.

Design patterns and pattern languages became a popular tool for software engineering in the 1990s. This is usually traced to Gamma et al. in 1995 [3]. Those patterns describe a repeated problem and the core of a solution to that problem class is their fundamental value. Gamma et al. tried to be more explicit than Alexander concerning the components of a pattern. Four critical elements were listed: the pattern name, the description of the ***problem***, the description of the ***solution***, and the consequences. A more detailed template was created, and their book [3], like the second volume of Alexander's work [2], provided a catalog of some discovered patterns, each entry describing a suitable problem space, the solution template, positive and negative consequences, and providing implementation advice. The popularity of software patterns led to further efforts to catalog patterns for software analysis [4] and design [5], and data models [5]. Discussions of negative patterns often found in systems or organizations were described as anti-patterns [6] with discussions of how to correct the problems. Conferences were held to capture the experience of practitioners in program design as a counterweight to scientific activities that focused on new approaches [7].

Ultimately, a pattern literature for HAT will accomplish the same goals that Alexander initially set out in the domain of architecture and land-use. Patterns serve to communicate generalized solutions to problems faced by engineers. Alexander believed that one could look through a catalog of patterns, identify the key features and forces of a project, and select the appropriate starting points to re-use the pattern. Then using the linkages provided among the patterns in his catalog one could bring in other appropriate patterns until one had a description of the solution in the form of a language of patterns. Our forces will include human performance issues, limitations of autonomy, communication issues, and many other critical factors. If our patterns can describe forces, features, consequences, and linkages to other patterns, pattern languages as solution descriptions may be possible within this domain.

4.2.2.2 Design Patterns in Human Factors, Ergonomics, and HAT

In the field of human factors and ergonomics, the description of design patterns also became fashionable recently. Borchers [9] is one of the first who described the linkage between human-computer interaction and design patterns. Kruschitz and Hitz [10] also provide a good overview. Kahn et al. [11] looked at design patterns for sociality in human-robot interaction.

Sheridan's well-known Levels of Automation (LoA) scale (e.g., Ref. [12]) is one of the early design patterns in human-automation interaction. System designers very successfully use this scale or one of its derivatives (e.g., Ref. [13], [14]) in many different application fields, sometimes even without knowing. In that sense, we see these kinds of Management-by-Consent-based / Management-by-Exception-based LoA scales as a collection of often-found design patterns. They apply for supervisory control relationships [12] between human and machine. In this use case, LoA scales provide an excellent source for deciding how to design the interaction for certain specific functions. Scales of levels of autonomy (e.g., Ref. [15], [16]) refer more to design options for the scope of a full system rather than single interactions. Their focus is predominantly on the description of the independence of the system from human intervention.

Juziuk [8] provides a comprehensive listing and overview of efforts to document design patterns in multi-agent systems. This gets us closer to what we need for HAT, in that cognitive agents and their relationships to each other are considered.

In the following paragraphs, we want to create a generalized framework and methodology for describing a wider variety of configurations in different scopes. We will present an approach to derive system requirements and to describe top-level system designs for systems involving HAT based on design patterns.

4.2.3 Basic Concepts

The traditional systems engineering view is solely on the formulation of requirements and the design of the technical functions of a system. The human operator only appears as an actor, usually located outside the system boundary. This approach is reasonable when automation is relatively simple, in the sense that it can perform specific clear-cut part-tasks. There, one can well describe the relationship between the (technical) system and the human user through use cases calling for a certain user-system interaction.

In this contribution, in contrast, we want to take account for the following trends:

- The automation in HAT will become much more capable in the sense of being able to perform higher cognitive tasks;

- The work share and interaction between the user and the automated system will be much less stable (e.g., adaptive automation [20]); and
- The task performance of human and automation will be highly dependent on a cognitive level. Hollnagel and Woods [21] speak of joint cognitive systems in this context.

Consequently, our approach focuses on two aspects:

- The description of the purpose we want to design a HAT system for, before the actual design; and
- The incorporation of the human user within the process and system boundary.

Hence, the following subsections follow a strict systems engineering top-down approach, also trying to establish a formal description language, semantical and graphical.

In a first step, we introduce the notion of the ***Work Process*** to develop an integrated view upon the purpose of a human-machine co-action, its physical and conceptional environment as well as its desired output to the environment the Work Process lives in. Connections and dependencies between multiple Work Processes may also be captured and described on this level.

In the second step, we establish a physical system instantiating the considered Work Process. We call this system a ***Work System*** in which the elementary roles of ***Worker*** and ***Tools*** are usually taken by humans and machines including conventional automation. This is a necessary and extremely useful step, because it allows incorporating classical human factors engineering approaches for systems with no HAT involved. The resulting ***human-machine system*** is already our first ***top-level design pattern***, acknowledging the assertion that there always a human shall be existent, controlling automated machinery, both constituting a most elementary Work System.

In the third step, we introduce "the autonomy" into the Work System, represented by one or more ***Cognitive Agents*** in various roles and relationships to the human operator(s), the conventional automation, and the machinery. At this stage, the design options in the different applications are plenty, however, still constructed of only a few elementary building blocks. Those building blocks, in our design pattern language, will be represented by a handful of the aforementioned ***semantical and graphical symbols***. The symbols stand for ***actors*** (i.e., humans, agents, conventional automation including machines), ***role allocations*** of actors (i.e., worker, tools), ***relationships*** among actors (i.e., hierarchical, heterarchical), and a few others (e.g., co-location, grouping). From the various application-specific Work System designs using those symbols in a coherent manner, we can now identify the same elementary ***{actor-relationship-actor}-tuples***, as we call them, again and again. Thereby, we can identify structural similarities in the sense of HAT patterns, to be discovered, over a wide range of extremely different applications and system design approaches. With this, scientists and practitioners can start identifying common or alternative solutions for similar problems, namely design patterns for HAT, and also conventional human-machine systems.

In the following sections the theoretical approach will be presented. The keywords of the language definition will be highlighted in `Courier` font. The graphical symbols will become clear in the figures.

4.2.3.1 The Work Process

The process of meaningful, goal-oriented co-action of humans (e.g., operators) and machines (e.g., Unmanned Vehicles (UVs) with automation), including artificial cognitive agents, shall be called a ***Work Process*** (`WProc`) (see Figure 4-1(a)). A ***Work Objective*** (`WObj`), i.e., the mission or the purpose of work, defines and initiates the

WProc. The WObj usually comes as an instruction, order, or command (e.g., a UV mission assignment). The proper definition of the WObj is of high priority and most critical for the definition of the system boundaries and the design. The WProc is embedded into a Work Environment (WEnv). WEnv inputs to the WProc are the physical Environment (Env) (e.g., atmosphere, threats), material and energy Supplies (Sup) (e.g., fuel, weapons), and Information (Inf) (e.g., ATC clearances, airspace regulations). Finally, the WProc generates certain physical or conceptual effects to the environment, i.e., the Work Process Output (WPOut) (e.g., target photo/video, destruction of target, provision of information to other WProc).

The WProc itself imposes meaningful actions upon a particular Work Object (WO) (e.g., target to be destroyed, materials to be transported, premises to be secured) being part of the WEnv. The WEnv may also host other WProcs. In case one WProc interacts with other WProcs, this can be organized as a hierarchical structure, i.e., a superior WProc generates the WObj for one or many subordinate WProcs and monitors their results, thereby forming hierarchical loops (see Figure 4-1(b)). Alternatively, the WProcs might be organized as a networked structure, i.e., parallel WProcs depend on each other in a way that their WPOuts cause environmental changes relevant to other WProcs, or provide supplies or information to other WProcs, thereby forming a more or less tight mesh of interdependently tasked WProcs, each following individual WObjs (see Figure 4-1(c)).

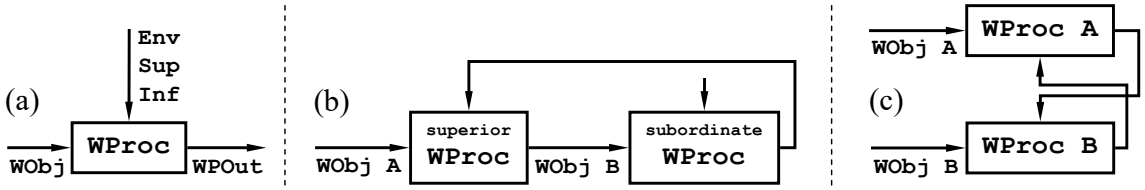

Figure 4-1: (a) Work Process; (b) Hierarchical Work Processes; (c) Networked Work Processes.

A proper work process design should be the starting point for each development of a system involving HAT. At this stage, *"it is more important to understand what the [... system] does [...], than to explain how it does it"* [21]. However, defining the WObj, the system boundary, and the interfaces of the WProc one wants to design for, is a hard task to do. The result will heavily influence the system design. From our experience in engineering HAT systems, we suggest a list of guidelines for the Work Process design as in Table 4-1.

Figure 4-2 shows an example of a common WProc design taken from civil aviation. The example consists of three individual WProcs, including the WProc: Airline Flight, which is the process we want to design a system for. This process changes the WEnv by transporting passengers (WO: PAX). It is in a hierarchical subordinate relationship to the WProc: Airline Dispatching that provides the WObj: Flight and supplementary information, and to which flight and aircraft status information are fed back. With the WProc: Air Traffic Control, a network is established, in which radar surveillance takes place, and requests and clearances are exchanged.

As already made clear, the specification of the WObj, and hence the WProc, is most crucial, since it describes the ***user requirements*** for a system to be designed. Consequently, a designer should make himself/herself aware that there exist different driving forces for considering a (new) WProc or WObj. In principle, we can distinguish two different design challenges.

Table 4-1: Guidelines for Work Process Design.

1) Identify the ***Work Objective*** (`WObj`) you want to design a system for.
• Therefore, describe the ***purpose*** your customer wants to achieve.
• Since we want to design a ***human-machine system***, it is always a good idea to start with describing the ***job of that human*** (team).
• If the human team members are working with very different or locally distributed workstations, ***consider*** defining ***multiple*** separate `WObjs` for hierarchical or networked `WProcs`.
2) Identify other relevant ***Work Processes*** (`WProcs`) your `WProc` is networked with.
• Therefore, consider ***agencies actively providing orders*** or commands to your `WProc`.
• Consider ***agencies actively providing*** relevant ***information*** or supplies to your `WProc`.
• Furthermore, consider agencies that ***receive*** the `WPOut` you are providing.
3) Draw a network of all relevant ***Work Processes*** (`WProcs`) including your `WProc`.
• Clearly denote the ***individual*** `WProcs`.
• Clearly mark the most important ***information flow*** through the network. Properly distinguish between `WObjs`, `WEnv` inputs, and `WPOuts`.
• This exercise will provide a good starting point for defining the inputs and outputs of ***your*** `WProc` (i.e., the `WProc` you want to design a system for) ***as a black box***. In this context, it might be helpful also to consider the introduction of a Work Object (`WO`).

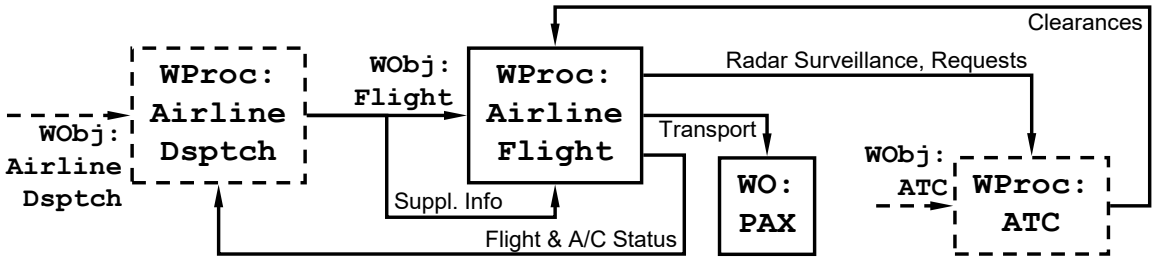

Figure 4-2: Example for a Common Work Process Design with Hierarchical and Networked Structures.

Firstly, the `WObj` is already clearly defined and kept unchanged during the design process. This is, for instance, the case for the `WProc` depicted in Figure 4-2. We have a relatively clear idea of the already in many instances existing `WProc: Airline Flight` and its today's implementation. However, there are still many technological efforts going on to further ***exploit***, aiming at one or more of the following:

- Higher effectiveness (e.g., by achieving more precise task execution, workload reduction, less human errors).
- Cost savings (e.g., by using fewer and/or less skilled operators).

- Improved safety and resilience (e.g., by improving the ability to cope with "what if" situations).
- Job satisfaction (e.g., by relieving from dirty, tedious, dangerous tasks).

Secondly, it might also be the case that someone wants to ***explore*** future design options. Let us think, for instance, of a `WProc` of controlling a fleet of unmanned airliners from a single ground control station. The resulting `WProc`, and therefore, the design of the system would be completely different from the one sketched in Figure 4-4, especially the design of the automation. Again, for such an endeavor, there would be a number of driving forces relevant. These, however, would go beyond those described before. Technological efforts striving for exploration will aim at one or more of the following:

- Operational benefits (e.g., by implementing a broader scope of a WObj made feasible for the individual).
- Economical rationalization (e.g., by overall reduction of personnel, i.e., WProcs to be set up).
- Business development (e.g., by exploring the potential to create and sell new products).
- Research (e.g., by exploration and extension of technological capabilities).

Self-evidently, the aforementioned goals of exploitation also need to be considered in design activities striving for exploration. Both, exploitation and exploration could greatly benefit from HAT approaches. The listed goals could serve as top-level drives for HAT design patterns.

4.2.3.2 The Work System

Now we are ready to open the black box. From now on, we look at the physical system that runs the `WProc` described so far (i.e., the system we want to design). We will name this a ***Work System*** (`WSys`), which already is our first ***design pattern***. It is important to note that the `WSys` inherits the complete definition of the corresponding `WProc` we described before. Within the box, in principle, there are two essential roles to be taken to run the `WProc`: the `Worker` and the `Tools` (see Figure 4-3(a)).

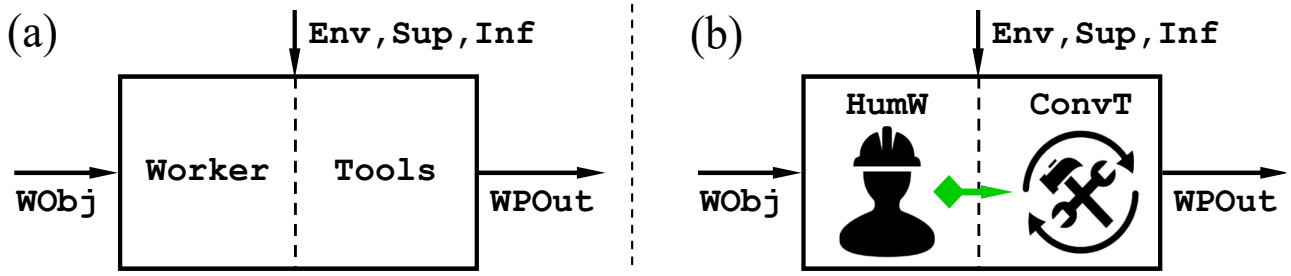

Figure 4-3: Design Pattern `WSys` as Physical Instance of the Corresponding `WProc`: (a) Comprising the Roles of the `Worker` and the `Tools`; (b) Instantiated with a Human Worker (`HumW`) and Conventional Tools (`ConvT`) in a Hierarchical Relationship (`HiR`, Green Arrow).

The main characteristic of the role of the `Worker` is to ***know, understand, and pursue*** the `WObj` ***by own initiative***. Without this initiative, the `WProc` would not be carried out. In all cases, the role of the `Worker` is instantiated with at least one Human Worker (`HumW`, see helmeted person icon in Figure 4-3(b)). Per definition, a `WSys` cannot exist without a `HumW`. Otherwise, we would not speak of a `WSys`, but rather of a

mere technical artifact, i.e., a (currently not used) Tool. Only Tools would not make a WSys, nor perform a WProc, due to the lack of purpose. The Worker, at the least represented by one HumW, is the only instance and responsible for breaking down the WObj into relevant tasks to be performed by, for instance, the use of Tools.

The Tools, on the other hand, will ***receive tasks*** from the Worker and ***will*** only ***perform*** them ***when told to do so***. Hence, the Worker and the Tools are always in a Hierarchical Relationship (HiR, see green arrow icon in Figure 4-3(b)). This HiR, among other options, will be characterized by more detailed design patterns at a later stage. In the context of our applications, the role of the Tools is usually instantiated by, what we call Conventional Tools (ConvT, see automation icon in Figure 4-3(b)). In this sense, ConvT are machinery and/or automation not capable of higher cognitive functions.

We would like to mention that in an earlier article [22], we defined "autonomy" by use of the WSys as the authorization of the Worker, again at the least represented by one HumW, to self-define the WObj. Only a HumW shall exercise this authority, for ethical and other reasons.

Traditionally, only a human or a human team represents the Worker. Machinery and automation would constitute the Tools. Thereby, a conventional human-machine system is created, involving manual control, and in presence of automation, also human supervisory control [12]. For these kinds of systems, we would use the role definition Worker and its instantiation HumW, as well as the role definition Tools and its instantiation ConvT in a mostly synonymous manner.

In addition to the conventional view if a supervisory control human-machine system, the notion of the WSys provides, further information concerning the WObj, i.e., the purpose of work, and the system boundary, including the definition of the interfaces to the environment. Finally, the Tools shall never contain a full WSys, or humans. From our experience, nested WSys are not a productive option. As an alternative, we recommend modelling the structure as a hierarchy of individual WProcs. In Table 4-2, we provide some guidelines from our experience for an initial WSys design.

4.2.4 Introduction of the Cognitive Agent into the Work System

With the advent of more advanced methods to provide higher cognitive capabilities on behalf of automated functions, the introduction of ***Cognitive Agents*** (CogA, little 'R2D2' in Figure 4-4) into the WSys becomes an option. In the past, the focus in this field was predominantly on the provision of suitable information processing methods and algorithms (e.g., artificial intelligence, computer vision, soft computing; cf. e.g., Ref. [23]). The introduction of such a CogA in a WSys, and one might want to have more than one agent in a system, substantiates the occupation with HAT-related problems and HAT patterns.

Two trends have been followed in the past two decades concerning the role such an agent could potentially take in system design. Firstly, so-called ***autonomous systems***, i.e., systems that aimed at performing user-given tasks, as much as possible independent from human intervention; and secondly, ***decision support, assistant, or associate systems***, acknowledging that a human predominantly performs the work, while supported by a machine agent [24].

Table 4-2: Guidelines for Initial Work System Design.

1) Transition from `WProc` view to `WSys` view.
   - The starting point is the `WProc` or network of `WProcs` you designed before. ***Each*** `WProc` ***will become a*** `WSys` keeping exactly the same specifications and periphery.
   - ***Open*** only the ***black box of your*** `WSys`, i.e., the `WSys` you want to design.
   - Keep all other `WProcs` (and also `WOs`, if needed) as black boxes. If you feel the urge to open one of them, consider a ***re-design*** of the network of `WProcs`.
2) Initial `WSys` design.
   - Populate the `WSys` with the necessary physical entities (e.g., humans, vehicles, control stations).
   - Start with the ***Human*** `Worker` (`HumW`) and the ***Conventional*** `Tools` (`ConvT`) (i.e., machines and automation not necessarily carrying attributes like "intelligent" or "autonomous") to develop a first product vision.
   - Take advantage of any available ***market solutions***.
3) Human-Agent / Human-Automation Task Allocation.
   - Now ***allocate the tasks*** you found in your task analysis to the `HumW` and/or automated functions. Some, unfortunately only very few, allocations are quite obvious due to their physical (e.g., aircraft flies) or legal/ethical (e.g., human decides on weapon deployment) requirements. However, many others are not!
   - If a task is undoable (by humans or system/automation), consider further breakdown of that task into subtasks.
   - The cognitive tasks, which turn out to be allocated to both, humans and automation (by sharing or trading) are the most interesting ones. They might require a ***cognitive agent***, and therefore, consideration of HAT.

We want to acknowledge these often-found trends by establishing two new elementary design patterns. Figure 4-4(a) shows a design pattern, where there exists a ***Hierarchical Relationship*** (`HiR`, green arrow) between the `HumW` and the `CogA` being part of the `Tools`. Within the `Tools`, a `HiR` (green arrow) between the `CogA` and other automated `Tools` exist. With this pattern the human will be able to offload portions of his mental work demands to a machine agent working in subordinate delegation mode. From a human factors stance, this pattern will mostly serve the design goals:

- To increase the human's effectiveness;
- To increase the human's span of control; and
- To reduce the human's taskload, and others.

Figure 4-4(b) shows a design pattern, where in addition to the `HiR` between the `HumW` and the `Tools` (cf. Figure 4-3), there exists a ***Heterarchical Relationship*** (`HeR`, blue connector) between the `HumW` and the `CogA` being part of the `Worker` in this case. Concerning this `HeR`, we would like to introduce one restriction, i.e., the `CogA` shall not be given the authority to define or even question the `WObj`. The `HumW` shall always have

the final authority do decide. With this design pattern the human cognitive performance will be supplemented by a redundant machine agent working in a peer-level assistance mode. From a human factors stance, this pattern will mostly serve the design goals:

- To avoid or correct human erroneous action;
- To moderate human mental workload; and
- To increase the human's situation awareness, and others.

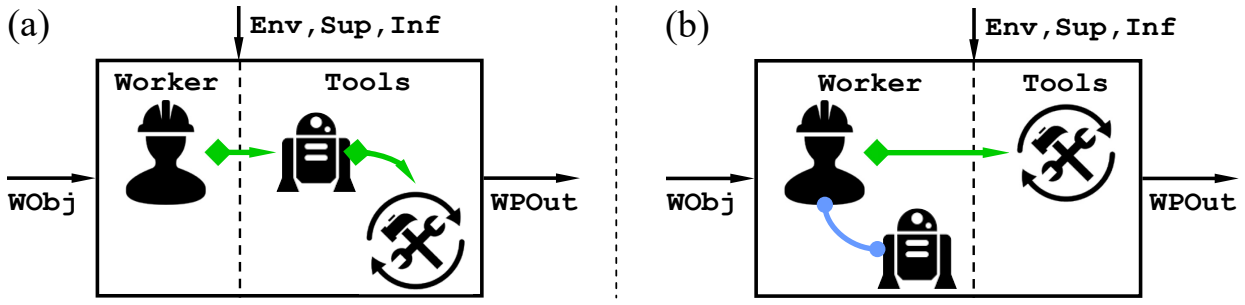

Figure 4-4: (a) Design Pattern `WSys` with `CogA` as `Tool` in `HiR`; (b) Design Pattern `WSys` with `CogA` as `Worker` in `HeR`.

Figure 4-5 shows some examples of existing setups we constructed using the elements `HumW`, `ConvT`, `CogA`, `HiR`, and `HeR`, all of which populate the roles of the `Worker` and the `Tools`.

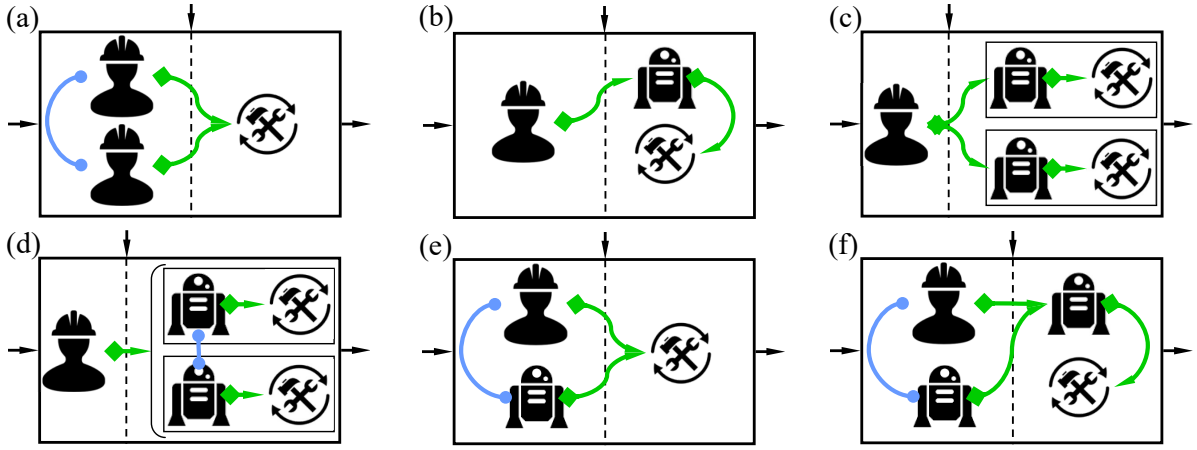

Figure 4-5: Examples for `WSys` Setups Constructed from the Elements Human `Worker`, `Tools`, `CogA`, `HiR`, and `HeR`.

- Figure 4-5(a) depicts a regular non-HAT system, in which two human operators cooperate while using technical equipment (e.g., a two-pilot flight-deck crew operating an aircraft). The two-humans option might be useful to reduce the individual taskload, or to increase the level of safety by implementing human redundancy.

- Figure 4-5(b) might be useful to either reduce the crew size (e.g., single pilot operations [25]), or to increase the span of control (e.g., larger "autonomy" of UVs [15]; single agent operation of multiple UVs [26]). In this case, the CogA is delegated certain tasks which otherwise a human crewmember had to execute.

In both examples, the effect could be mostly attributed to a reduction of the taskload of the HumW. Elements of adaptive functional allocation might also be involved [27].

- Figure 4-5(c) is an extension to Figure 4-5(b) where there is more than one agent tasked by a human operator, each controlling its individual physical system (e.g., task-based guidance of multiple UVs [28]). Again, the challenge here is the increase of the span of control by means of spreading the taskload. The necessity for more than one CogA might be generated by the physical co- or dis-location of the ConvT (e.g., a multi-robot system). In our graphical code, co-location shall be visualized by a box.
- Figure 4-5(d) goes even further down that road. Here, the human user controls a cooperating team of multiple agents (visualized by the bracket), each of which operating its own equipment (e.g., pilot controlling a cooperating team of multiple UVs [29]; multi-agent system controlling multiple UVs [30]).

However, an increase of automation complexity and span of control, as exercised in Figure 4-5(b) through Figure 4-5(d), may also result in automation-induced shortcomings. These effects have been reported by many researchers (e.g., Ref. [31] for a classical source).

- To counteract such problems, a number of scientists suggested approaches as in Figure 4-5(e). Here, the agent works in cooperation with the human operator being an element of the Worker (e.g., pilot assistance or associate systems [32]). Core elements here are the agent's initiative in achieving the WObj, and the ability of the agent to decode the human's mental states as a basis for cooperation. Means of assistance can be attention allocation, mixed initiative operation, and adaptive automation techniques [20].
- Finally, Figure 4-5(f) shows a setup, in which a human is controlling a system via agent delegation, while at the same time being assisted by an agent being part of the Worker (e.g., assisted guidance of a single UV operator [33]; assisted multi-UV mission management [34]). This pattern combines benefits of Figure 4-5(b) and Figure 4-5(e).

In the two latter cases Figure 4-5(e) and Figure 4-5(f), where a CogA is part of the Worker, the CogA inherits the required attributes of the role of a Worker as claimed in Section 4.2.3.2, i.e., to know, understand and pursue the WObj by its own initiative [22], [24].

At this stage, it is obvious that there can be constructed many more configurations, especially when we look at distributed multi-user, multi-agent systems with complex HiR/HeR structures.

4.2.5 Actor-Relationship-Actor-Tuples

As became clear during the discussion in the previous paragraph, there are possible very many WSys configurations only by combining one or few of the elements provided (i.e., HumW, CogA, ConvT, HiR, and HeR). Thereby, researchers and practitioners can depict their individual approaches described in literature, and hence, make them comparable. In this paragraph, we now want to look at the possible ***{Actor-Relationship-Actor}-tuples***, which can occur in the various WSys. Figure 4-6 gives an annotated overview of all possible tuples. Here, the possible actors are HumW, CogA, and ConvT; possible relationships are HiR, and HeR. The HumW will, per definition, always take the role of a Worker; the ConvT will always be Tool, whereas the CogA may take the role of a Worker or of a Tool. Between a Worker and a Tool there will always be a HiR.

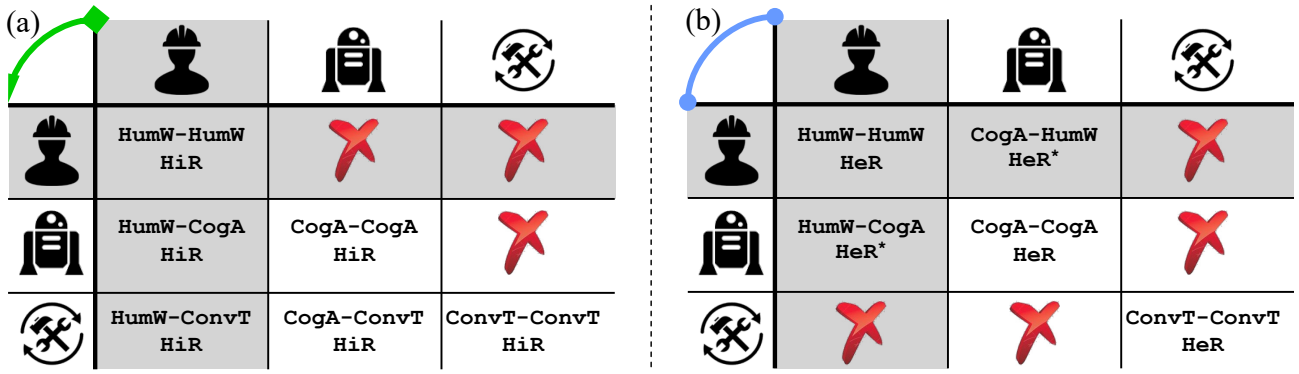

Figure 4-6: (a) Hierarchical; (b) Heterarchical {`Actor-Relationship-Actor`}-Tuples; (Shaded: Human Involved; *: Equal Configurations; Xs: Invalid Option).

Figure 4-6(a) shows all possible hierarchical {`Actor-Relationship-Actor`}-tuples.

A hierarchy of a `CogA` or a `ConvT` over a `HumW`, or a `ConvT` over a `CogA` we do not want further to consider. The same applies to a heterarchy of a `ConvT` with either a `HumW` or a `CogA`, for obvious reasons. Tuples, which do not involve humans, may not directly be interesting for HAT systems. However, they certainly can influence the behavior of the automation "under the hood", and therefore, be worthwhile to look at, at least from a pure engineering stance. Also, the pure human-human relationships, either hierarchical or heterarchical, may not directly be relevant for HAT systems, except of course for `WSys` with more than one human. Apart from that, they may serve as valuable source for design metaphors. Finally, we do not want to allow a Human-Agent `HeR`, where the agent is part of the `Tools`, since per definition there is always a `HiR` between `Worker` and `Tools`.

Within the scope of the modelled `WSys`, the {`Actor-Relationship-Actor`}-tuples describe the binary relationships between two entities. The possible combinations include tuples with well-established design patterns.

The tuple {`Human-HiR-Tools`} describes the basic setting of human supervisory control [12]. By the time when Sheridan established his LoA scale, automation used to be mostly rather clear-cut control automation following relatively simple rules or algorithms. In most of these systems, the human exclusively owned higher cognitive capabilities. It was acknowledged in later works [13] that automation could also take over higher cognitive tasks. New scales for LoA have been developed (e.g., Ref. [13], [14]), which, to a certain degree, reflect the situation that automation became capable of assuming functions of information acquisition and analysis. These scales are applicable to the tuple {`Human-HiR-Agent`}. Since then, many works have been conducted, supporting the relevance of this tuple and provide valuable design patterns (e.g., Ref. [26], [28], [35]). Van Breda and coauthors also provide a good overview [36].

Finally, the {`Human-HeR-Agent`}-tuple has become particularly interesting in situations where automation-induced human erroneous action should be prevented. We already mentioned a few citations in this context [22], [24], [32], [33], [34]. Also further international approaches to adaptive associate systems should be mentioned that are representative to many others [37], [38].

4.2.6 Conclusions

In this section, we describe a method for documenting Human-Autonomy Teaming (HAT) design patterns. Therefore, we followed a strict top-down procedure, inspired by systems engineering and cognitive ergonomics. Coming from a general human-systems view, we ended up at the level of frequently recurring actor-relationship-actor-tuples, which may serve as containers for similar or competing design patterns to be found, described, and discussed. However, the benefit of this approach heavily depends on the researchers' and practitioners' efforts to describe their solutions to HAT problems using the offered method. In doing so, we could avail of a great opportunity for rational discussions on future highly automated systems.

4.3 POTENTIAL SOLUTION 1: COMMUNICATION MANAGEMENT

4.3.1 Intent

Allow humans to team effectively with automation through the development of a communication channel. This allows the human (and automation) to question each other, share hypotheses, provide additional input, etc., just as human teammates would.

4.3.2 Motivation

Teammates often discuss options, brainstorm on solutions and openly discuss courses of action. For automation to be on a team, this bi-directional communication needs to exist. Bi-directional communication is key to solving a number of the issues typically found in highly automated systems. Bi-directional communication can make systems more transparent and less brittle, and further, can facilitate intent-based interface design.

If automation (or people) did not make errors, such communication would be unnecessary. However, both humans and automation are prone to make planning errors, albeit different types of errors. Automation can make precise calculations and use them to accurately follow rules when they exist. However, it can only account for information it has specifically been designed to look at and will follow rules even when the rules have not been validated for a specific combination of factors. Humans can take into account new, arbitrary information and process it holistically. However, they cannot equal automation's precision and often focus on one factor while forgetting about others. This pattern enables communication of information relevant to decision making, planning, and execution between human operators and automation to improve performance over what either the operator or automation could achieve. In particular, this design can overcome a number of problems encountered when automation is implemented without bi-directional communication such as:

Brittleness: Automation is designed for a certain environment. True, that environment might be fairly general. An automated car, for instance, might be designed for a wide variety of driving environments. However, when placed in an environment that the designers did not anticipate, maybe a white panel truck having the same color as the sky turning in front of it, the results can be catastrophic. Similarly, automation may break down in unusual (and thus poorly tested) situations. Humans, generally, are better able to adapt to unfamiliar situations. Having human operators work with the automation allows them to supply missing information or context and, if necessary, override the decisions made by automation in these situations.

Lack of Transparency: It is often unclear why the automation is taking the actions that it is. This inhibits the operator from analysing whether the actions taken by automation are appropriate.

Inappropriately Calibrated Trust: If the operators do not understand why the automation is taking the actions it is taking, they may not be able to determine when they can rely on the automation. If operators do

not trust the automation when it is supplying correct information, they may not use it, undermining the reason for having the automation. Conversely, if operators trust the automation even under conditions where the automation lacks information necessary to perform adequately, severe problems may result.

Lack of Shared Awareness: If the automation and the human operator do not have a shared model of the task and situation, the automation may act in ways that the operator does not expect. This might result in reduced trust and disuse if operators decide to opt for courses of action that they can understand or predict, or it could result in over trust and complacency if operators decide that the automation must know what it is doing and quit monitoring it because monitoring does not help if one does not understand why it does what it does.

Lack of Situation Awareness: Because, with traditional automation, either the automation or the human operator "owns" particular tasks, the operator often does not have or does not pay attention to information relating to tasks delegated to the automation. This results in a lack of situation awareness regarding these tasks that can cause major problems if the automation cannot cope with a particular situation (see Brittleness above) [39].

4.3.3 Applicability

This pattern facilitates sharing of information regarding problem definition, potential solutions and authority to act. Such information has been shown to be critical in a wide variety of situations.

4.3.4 Structure

Managing bi-directional communication relies on dealing with a dialog protocol. This protocol can be structured according to the following diagram (see Figure 4-7), while distinguishing three aspects respectively devoted to the content, the timeline of communication and the modalities of dialog and communication.

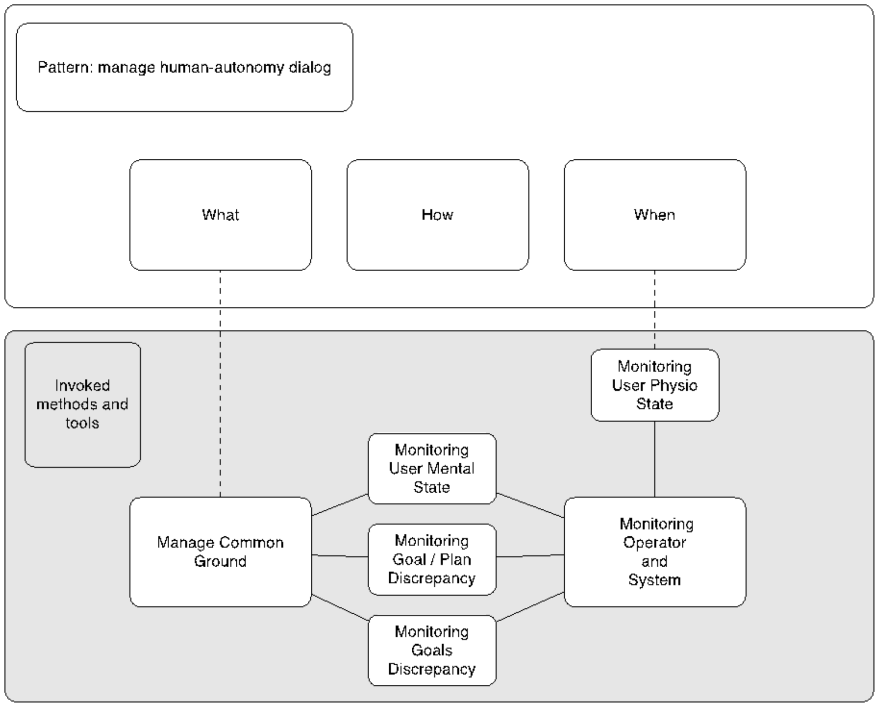

Figure 4-7: Diagram Representing Dialog Management.

The question of what is communicated is broken down further in Figure 4-8, which describes what types of information need to be shared between automation and the human operator (across the bi-directional communication channel).

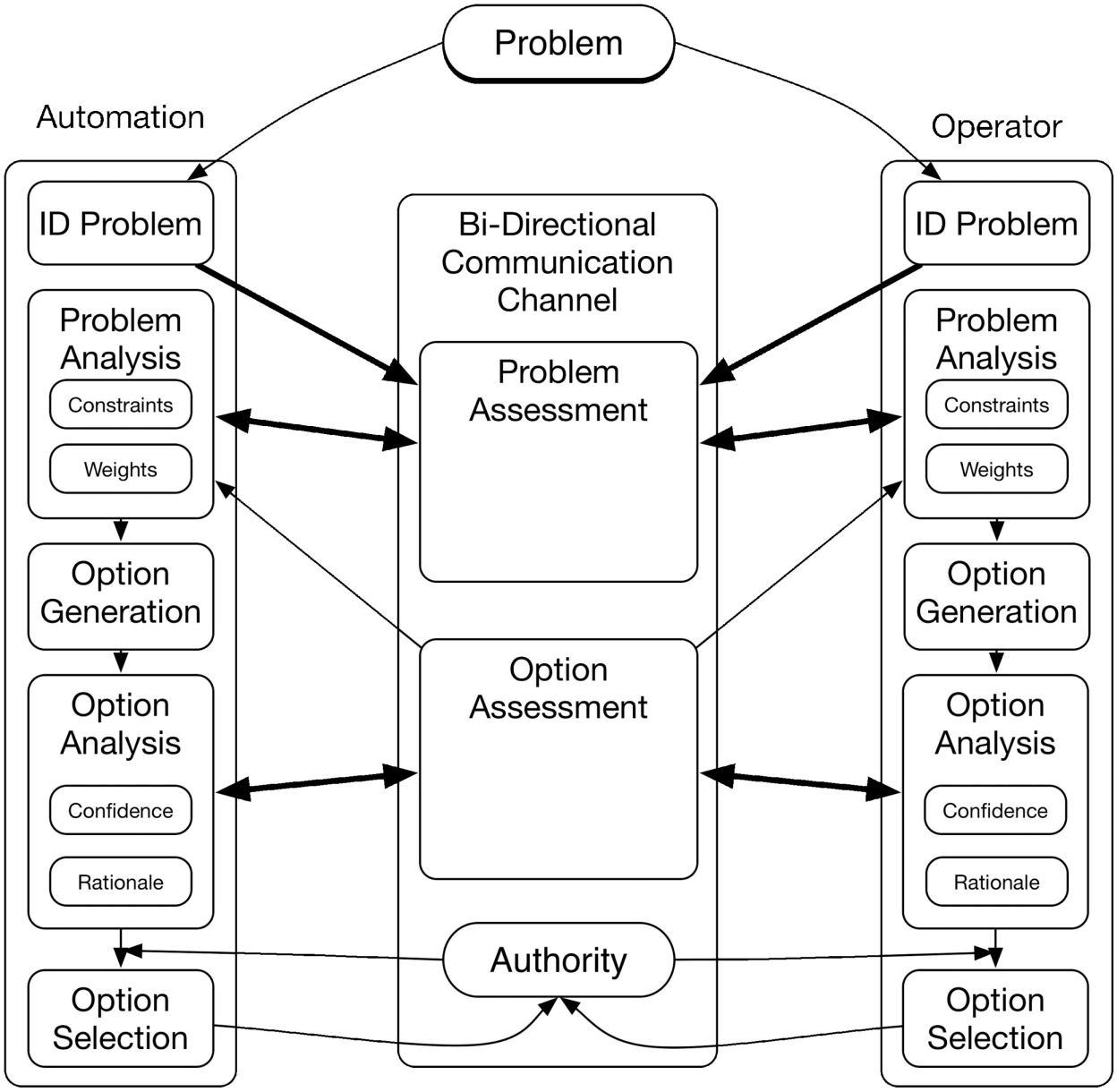

Figure 4-8: Bi-Directional Communication Channel Between Automation and the Human Operator.

We have divided the information that needs to be communicated into three categories: Authority (what level of automation should the automation be working at?), Context (what problem / what goals are the human and automation attempting to work on?), and Options (how could we achieve our goal or solve our problem?).

Level of Authority/Delegation: One crucial piece of information that needs to be communicated between automation and the human operator regards authority. This could be as simple as whether the operator or automation is performing certain tasks. At a slightly more complex level, we can imagine assigning the automation intermediary Levels of Automation (LoA); e.g., the automation chooses a course of action which it implements unless vetoed by the operator). As automation gets more complex, however, we envision a more complex authority structure. For instance, automation may be assigned more complex "working agreements" like contingent LoAs (e.g., execute the plan autonomously unless the uncertainty about the outcome exceeds a certain threshold). Using such automation, human operators will need access to this information and will need to be able to adjust the working agreements for determining authority.

Context: Teaming must occur within a context, and this must be understood by both automation and human operators in order to act effectively. This context must include some sort of goals or cost function and constraints that may reflect a problem or perceived threat (e.g., lower than expected fuel score, anti-skid inoperable indication), opportunity (e.g., dissipation of a thunderstorm that allows more direct routing).

- **Goal/Mission:** In order to team effectively, teammates need a shared goal or mission. Goals may fall into hierarchies, both in terms of subgoals that must be achieved to reach the main goal (the goal of winning a war, involves subgoals of winning individual battles, which have subgoals of positioning troops, etc.), and in terms of value (routing the enemy is better than being stalemated which is better than being routed oneself; when the most valuable goal cannot be achieved, one often has to fall back). If these goals, subgoals and fallbacks are not shared by both parties, the "team" can find itself working at cross-purposes. As part of the goal, it is important to indicate when a solution is "good enough" (satisficing).
- **Constraints:** A given situation typically comes with some constraints that rule out certain solutions (or, at least, make them categorically worse than others). For example, an aircraft cannot divert to an airport that is outside its fuel range. Perhaps less obvious are constraints that can be violated. For example, it is "illegal" to land at an airport with visibility below a certain level. For instance, there is not necessarily a major jump in risk between landing with 500 m visibility and landing with 400 m visibility. Yet, in one case the pilot may have to declare an emergency and take other actions that make the former significantly more desirable than the latter.
- **Weights:** In addition to constraints, there are other factors that can be more naturally traded-off against one another. If a passenger has a heart attack, it is important to get the passenger to sufficient medical facilities as quickly as possible. That is great if the closest airport also has the best medical facilities, but if it does not, how much time can one give up in order to get better facilities? Weights allows the operator to define a function across the different factors that go into their decision, communicating to the automation how much the operator cares about these different factors.
- **Temporal:** Information relevant to the timing of events and planned actions must be understood by both the automation and the operator. One issue is how quickly actions need to be taken. There are constraints on both how long the current state can be allowed to persist before an undesirable outcome (e.g., how long can a pilot delay putting out speed brakes before going overspeed), and also how long particular options are no longer viable (e.g., if I am in the left lane on the freeway I might need half a mile advance notice to get over or I will miss my exit). These timing issues may also affect the type and amount of information presented as, under sufficient time pressure, it may not be possible to absorb more than they most critical information. Temporal information is also important in the timing of information presentation, especially aurally. Information presented while the operator is performing other actions may both interfere with those actions and be forgotten when the operator does get to performing the associated operations.

Options:

- **Projected outcome:** In assessing options, it is important to understand the projected outcome. This goes beyond whether the goals are achieved and the constraints met. Operators need to understand the state they will find themselves in, for example, landing an aircraft the operator should know fuel at landing, ETA, etc.
- **Confidence:** In evaluating options generated by another teammate, it is important that one understands the confidence in that solution. This is especially true when the other team member has access to information or processes that you do not share. This will often be the case in human-automation teams where the two team members have very different abilities to sense and calculate. (What are the odds that this solution is the best? What are the confidence intervals on ratings of the options? What are the odds that an option offered will, in fact, work?).
- **Rationale:** One of the primary motivations for HAT is to create systems that are less brittle than current day automation typically is. This is achieved, in large part, by having human operators better understand what the automation is doing so that they can see gaps in its planning. To do this, however, the operator must understand the why the automation is doing what it is doing. These rationales can come in different granularities (e.g., "diverting to DEN has the lowest risk score," vs. "DEN is CAT III capable so you can land there even if the weather deteriorates farther").
- **Coherence:** Automation may be able to detect whether options fail to meet certain standards and flag those that do not. These standards could be established rules (e.g., failure to meet a restrictions flight restriction), or the normal behavior of the operator or other operators in similar situations ("you / other operators have rejected this option on other occasions").

4.3.4.1 Functional Structure of the Pattern

4.3.4.1.1 Function 1: Monitoring Operator Mental State

Objectives: Set a (real-time) profile of the operator(s) so as to feed the protocols of communication consequently. The profile is dealing with cognitive load and performance, but could as well integrate some emotional state that could impact the style and etiquette used for communication.

Inputs:

- Physiological measurements.
- Operator's performance assessment.
- Operator's strategies measurement.

Outputs:

- Evaluation of operator's functional states (binary or discrete scale, to be defined).
- Evaluation of operator's emotional states (taxonomy to be fixed, emotions, moods, attitudes).

4.3.4.1.2 Function 2: Manage Timeline of Communication

Objectives: The time dimension of communication may impact / be impacted by cognitive workload as well as the evolution of situation. When the operator is overcharged, there may be a need to postpone the communication of non-priority information (as well as a need to choose an adequate form of communication,

see Function 3). Criticality of information and alerts, as well as operators' priorities are also to be taken into account to deal with time of communication.

Inputs:

- Situation assessment and detected discrepancies (new objects, conflicting objects, conflicting priorities, etc.) – provided by external pattern devoted to Situation and Common Ground assessment.
  - Alerts;
  - Missing information (from machine point of view); and
  - Errors, etc.
- Authority assessment.
- Operator functional state (Function 1).
- Operator emotional state (Function 1).
- Timeline of reference (imposed protocol of communication).

Outputs:

- Recommendations concerning time to communicate about elements.

4.3.4.1.3 Function 3: Manage Content and Style of Communication

Objectives: The level of detail and style of communication depend on the context and state of the operator. In a low cognitive workload case, it can be proposed to communicate explicitly about the different elements of situation or authority delegation. With a more severe workload, other solutions (color codes, dedicated modalities, etc.) can be preferred. Weights and priorities may also be used to filter the relevant messages to be communicated. Based on outcomes from the Transparency Pattern, some levels of explanations may be chosen depending on the context and nature of information.

Inputs:

- Situation assessment and detected discrepancies (new objects, conflicting objects, conflicting priorities, etc.) – provided by external pattern devoted to Situation and Common Ground assessment.
  - Alerts;
  - Missing information (from machine point of view); and
  - Errors, etc.
- Authority assessment.
- Operator functional state (Function 1).
- Operator emotional state (Function 1).
- Timeline of reference (imposed protocol of communication).
- Level of detail and explanations to be used (provided by Transparency Pattern).

Outputs:

- Subset of information to be communicated.
- Style of communication (etiquette, mode of communication).

4.3.5 Participants

Human Clients:

- Sets/validates mission goals.
- Sets/validates working agreements.
- Proposes/validates Courses of Action (CoA).
- Implements (all or part of) CoA.
- Monitors for Errors.

Automation Clients:

- Validates mission goals.
- Validates and proposes to working agreements.
- Proposes/validates Courses of Action (CoA).
- Implements (all or part of) CoA.
- Monitors for Errors.

Communication Manager (agent):

- Maintains and presents goals, working agreements, courses of action, and alerts in a context sensitive and progressively discoverable manner.
- Tracks progress toward goals.

4.3.6 Collaborations

- Clients (Human and Automation) publish information (goals, working agreements, courses of action, alerts) into the communication channel.
- The communication channel makes this information available to clients. Depending on context, this information may be pushed (e.g., alerts) or may require that the client request it.

4.3.7 Consequences and Justification

Proper implementation of this pattern mitigates the problems noted in Section 4.3.2 above:

Brittleness: By enhancing communication of both situational variables and potential courses of action, implementation of this pattern allows the human operator to recognize situations where the automation is operating outside its design space and either provide it with additional information or alternative courses of action, potentially executing the latter manually if that exceeds the automation's capabilities.

Lack of Transparency: Increasing transparency is, of course, the most direct consequence of implementing this pattern.

Inappropriately Calibrated Trust: By increasing the communication of information regarding how automation arrives at particular courses of action, implementation of this pattern allows human operators to recognize when automation is developing a course of action that is appropriate to the circumstances and when it is not. Such recognition, in turn, allows operators to comfortably trust and rely on automation when it is most likely to provide correct guidance and to distrust it under conditions where it becomes increasingly less reliable.

Lack of Shared Awareness: When the automation and the human operator have different information, the automation may act in ways that the operator does not expect. Implementation of this pattern reduces this issue by requiring that the automation make available to the operator its model of the operational environment and the reasoning behind any proposed or selected course of action. Thus, it should be apparent to the operator why the automation behaves the way it does. Further, implementation of this pattern allows the operator to give the automation relevant knowledge that may allow it to behavior in a manner more consistent with the operator's understanding of a given situation.

Lack of Situation Awareness: Implementation of this pattern does two things to increase the human operator's situation awareness. First, it creates a more transparent system, where information relevant to the performance of automated tasks is readily available to the operator. Second, it breaks down task allocation so that operators are, to some degree, involved in tasks that would be fully automated under conventional approaches to automation. This involvement keeps the operator in the loop and thus better prepared to react in situations where the automation fails.

There is one major negative consequence to implementing this pattern: the required increase in communication adds to the time required to make decisions. Thus, in time critical situations it may not be advisable to include robust bi-directional communication. However, it is possible to use the working agreements pattern, it is often possible to take much of this communication burden "offline" by building working agreements that enable efficient communication of the most critical real-time elements and allow for automated actions based on those communications (see Ref. [40]).

4.3.8 Implementation

Dealing with operator mental states may generate some difficulties in applying this pattern, as physiological and behavioral data processing techniques have not achieved a high level of maturity. The mining of EEG signals as the stability and reliability of complementary physiological signals (skin conductance, or even ECG) may raise questions of applicability of the approach. It is suggested to remain modest in the expected categorization of operator states, as well as to rely as much as possible on multiple sensors to make more robust classification and interpretation. The same kind of remark may be applied to operator's emotional state, which is even more difficult to define and measure in a stabilized way.

When managing the style of communication, one can refer to etiquette theory. This approach may strongly differ from one culture or context to another, so that one should remain cautious about relying on styles that would be too caricatured (hierarchical and commander style, friendly and informal style, etc.).

This pattern levies certain requirements on the automated systems. The automation must have a certain level of self-awareness to provide estimates of how accurate (and how confident it is) in its options. Further, the automation must have insight into its reasoning to be able to explain its self to the human team mate. In some systems that use genetic algorithms and neural networks, this may be more difficult.

4.3.9 Examples and Known Uses

We are not aware any robust implementations of bi-directional communication between human and automation teams. As a preliminary implementation, we have conducted a simulation which incorporated bi-directional communication, among other proposed HAT tenants, into a ground station with an automated recommender system used by a ground operator to support multiple commercial aircraft in high workload and off-nominal situations. This study is discussed in more detail in Section 5.7 and in Ref. [41].

Our automated recommender system was designed to support rapid diversion decisions for commercial pilots in off-nominal situations. To support bi-directional communication, we provided preset weights for each play (a play defined operator and automation tasks) and presented the weight settings to the operator. The operator was able to negotiate with the system by changing the weights to better fit the situation and could adjust the weights to see how the divert recommendation might be affected. For example, in a Medical Emergency play, more weight was given to the estimated time of arrival and services provided than fuel consumption. Participant feedback supported the use of weights to improve automation's ability to handle unusual situations and were useful in making divert decisions.

4.3.10 Related Patterns: Similar or Usefully Paired

Transparency: This pattern uses the Transparency Pattern to allow the operator to understand the evaluations made by automation. This is necessary for the operator to adjust the pattern should the automation find patterns produced by the operator unsatisfactory.

Goal Setting: While the Negotiation pattern can be used under conditions where the operator and automation have distinct goals (e.g., the operator might be responsible for safety and the automation might be responsible for efficiency), it is often more efficient to have the operator and the automation propose and evaluate patterns based on the same goals. To do this use the Goal Setting pattern.

Working Agreements: As noted in the section on consequences (see Section 4.3.7), one side effect of implementing this pattern is to increase decision times, making it potentially undesirable in time critical situations. Lachter et al. [40] note that in many situations it may be possible to move much of the extra communication time out of time critical periods, by using the working agreement pattern [42]. For example, an automated navigation system for an automobile might want to reroute you due to traffic. In this case it may not be feasible to fully vet the suggested route, especially if the human operator is currently tasked with driving. However, a working agreement could be established before the trip is embarked upon, that codifies what the operator considers an appropriate reroute. In this case the vetting can happen "offline", before the time critical phases of the trip.

4.4 POTENTIAL SOLUTION 2: DESIGN PATTERN FOR WORKING AGREEMENTS

4.4.1 Intent

Humans and machines are increasingly reliant upon each other in complex environments and military operations. The near future suggests human understanding of machine counterparts is a required, paradigmatic element. Knowing how to engineer and design for these environments is challenging. The complexity between levels of automation, human information processing, and function allocation authority issues in an adaptive system make it unlikely to find a "one-size-fits-all" approach. There may still be general strategies for engineering in these cases; for example, collaborating and coordinating are familiar requirements of all human team activities, and extend to human-automation teaming. Here, we outline a pattern for working agreements.

Agreement Patterns are used in a variety of different ways to define patterns for sharing and reusing previous experiences in the application of agreements. *Negotiations*, which can be classed as a type of agreement, are usually conducted between humans. This section uses the agreement patterns concept and applies it to a negotiation in order to aid with human-autonomy teaming within a military domain. In addition to negotiation, a *commitment* pattern can be applied to define the permissions, prohibitions and obligations in a normative framework.

4.4.2 Introduction

> *Agreement technologies do not dictate the underlying technologies (objects, components, agents, services, ...), but are focused on the formalization of knowledge structures, protocols, algorithms and expertise that contribute to the establishing of Agreements.* [43]

Working agreements define how and when human-automation teams split tasks, and in what situations responsibilities over these tasks may change. Most of the power of using agreements is in reducing the mismatch between different agents' expectations about the state of the world, and how agents will interact; and the true state or operating model of the agents, which drive intention, and action. The mismatch between how agents represent other agents expected behavior might affect both the human and any automated participants. Often times this mismatch creates serious safety and performance failings, such as the grounding of the ship Royal Majesty. The inability of the crew to confirm that differential modes of automated navigation and GPS navigation information were active and valid [44] created serious issues. The combination of mode confusion, automation surprise (because of mismatched user-machine models of the environment and how each agent should work), and embedded automated commands operating silently, led a simple GPS receiver loss while leaving a harbor to metastasize into a catastrophic grounding of the ship many days later [44].

Working agreements may improve the transparency of automated decision-making systems by clearly indicating, as well as pre-determining what tasks each human and automated agent in a team performs, and under what conditions. Working agreements can even specify particular methods for solutions that could be used, or could not be used or allowed.

Working agreements seem especially appropriate for teaming, as team situations require communication and collaboration [45], [46], [47] in a way that is facilitated by:

a) Articulating tasks and functions;

b) Properly allocating those functions among members; and

c) A display of the allocation of tasks among the team [48], [49]

For example, managing tasks is a source of difficulty for supervisory control of unmanned systems. Automation may reduce load by taking control of some of the operators' tasking (thus reducing demand). The tasks themselves form the backbone of an agreement, which can be configured and determine the behavior of the agents.

Still, certain tasks may be off-limits to certain actors (for example, weapons release). A working agreement could specify tasks that the automation cannot or is not allowed to perform. However, a conditional property may modify such an agreement – which can be specified as well. The key is that these conditional function allocations are brought to the surface of human-automation interactions, where they are visible and, if appropriate, adjustable. This way, working agreements can help to meet four challenges of human-autonomy teamwork: trust calibration, context-adaptive coordination, dynamic task allocation and persistent norm compliance [50].

In military operations, negotiations are used frequently in order to complete certain protocols and procedures. These negotiations are often repeated, albeit that the context maybe different. The formats of many procedural negotiations are derived from various policy documents applicable to the operating context, which in this case is the operation of military air platforms. Policies applicable to this context range from international civil regulatory policies for operating air platforms in different classes of airspace, through to military platform-specific Techniques, Tactics and Procedures (TTPs). These policies typically include guidance or instruction on when negotiations need to occur, the format of the negotiation, and in some cases a range of allowable content (for instance a negotiation being required between air platform operator and Air Battle Manager prior to entry of the air platform into controlled airspace).

4.4.3 Motivation

Working agreements help make the rules and constraints of human-machine teams explicit. It is especially important to articulate constraints when the roles and responsibilities of automation "adapt" to changing conditions of the operator and/or the environment. The notion of adapting responsibilities between humans and automation differs from traditionally "static" automation (e.g., Ref. [51]). Adaptive automation attempts to deal with the complexity and context-specific dynamics inherent in real-world system operations [51]. These situations are often large, complex, and rapidly overwhelm the limitations of human memory and attention [52]. Such adaptive automation seems to be the future of most systems due to greater success than seen in other automation implementations [53]. As working agreements help track and specify the changes in authority and responsibility that accumulate across adaptive systems, they are naturally beneficial.

Many have written about the intricacies of determining how and when automation changes its behaviors [54], [55], [56]. In considering how systems should adapt and interact with operators, working agreements could become a centerpiece in making explicit the capabilities and limitations of the automation (and aiding in developing operator expectancies by making them explicit). As a direct effect, human memory demand is reduced through a better, more available representation of what the automation is doing, and when. Most important is that the negotiation between systems and operators about task and function allocations can happen before workload reaches a high level [57], [58], when most traditional solutions would take effect.

There are several key characteristics to a working agreement in human-machine systems; the use of adaptive or adaptable "mixed initiative" automation with multiple actors; a base model to represent the automation capabilities and limitations; and a triggering model in the case of adaptation for representing how and when to shift responsibilities between the human operator and the system. Adaptation in this sense represents an update of who is responsible for what, in real time, and adjusting the associated information displays, task sequences, and task deadlines as required [59].

Explicit definition of goals and tasks, and how they are shared and split between the agents, are necessary steps toward developing good teamwork and communication (e.g., Ref. [18], [21]). These same sets of goals and tasks can populate a working agreement structure [17], [60]. They are, in some respects, necessary before a working agreement can be developed, and are at least one way to abstract the tasks, and the methods to accomplish them, in a manner that a machine may understand and process [61].

In the case of working agreements, automation transparency should also be increased. The task-based nature of working agreements helps indicate in clear language what the automation should be doing in any foreseeable condition. Tasks and methods to perform them can also be specified in system language, providing some shared understanding. Working agreements will not solve emergent issues that complex systems may create which are not foreseeable. Different methods may be useful for creating teamwork between humans and artificial neural network-created behaviors, for example [62].

Limitations of the automation can also be articulated in clear task-based language. The system can no longer hide which tasks it is, and is not, performing or going to perform. Allocations are displayed to the operator prior to performance, aiding in transparency and operator trust.

Working agreements may also be available during or displayed after performance to aid in training and building of user mental models. The agreements themselves may be useful when aggregated across a range of users; for example, did Bob set up a different agreement than Jill? What conditions prompted the difference? Were there any performance effects as a result? While there is a myriad of ways to improve operator trust or acceptance of automation behaviors, working agreements may be one of the easier methods to implement, once a task taxonomy is created and methods of performance are cataloged.

4.4.4 Applicability

The working agreement pattern should be useful when there is at least one human and one computer "agent," each of which may be asked to perform tasks and occasionally share or trade responsibility for their execution. Such configurations are often referred to as adaptive automation [53] or sometimes adaptable automation [55], or mixed initiative automation systems. In each, there are definable tasks that either the human or the automation can perform. Additionally, their name hinges on the locus of the allocation authority [63], either human "adaptable," or computer "adaptive," systems.

The allocation agent is that which decides how to allocate task responsibility between the participants. The allocation authority, if a computer, can assign incoming and existing tasks based on any number of inputs of varying complexity, including human workload estimation [56], [64], [58] or state changes in the system given a set of parameters. For example, the flight management system – autopilot – in some airliners takes action at the point in landing where human reaction time is subpar and unsafe. The function is allocated to the computer and taken out of the hands of the human, based on a condition; [65]. If the allocation authority is a human, then the human directs other humans and automation to have responsibility over certain tasks.

4.4.5 Participants

4.4.5.1 Human Operator(s)

The human operator determines and sets the base configurations of the working agreements. These include more than just the function allocation elements. Configuration of the working agreement also involves determining the transition points and conditions that may serve to alter function allocations and authority changes to particular elements, classes of elements or more. The involvement of actual end users in this effort is critical to avoid confusing future operators, or anchoring design around inappropriate elements or triggers. Multiple cognitive task analysis methods are available to help determine these [66], [67], [68].

As we will discuss in a later section, human-human working agreements are already a familiar concept in some domains. The extension of the design pattern to human-agent and human-autonomy teams is a natural one, and is being explored.

4.4.5.2 Autonomy / Intelligent Agent(s)

An intelligent agent must be able to interpret the human's determination and setting of default working agreement configurations, including function allocation, and transitioning conditions (usually based on if then logic).

4.4.6 Structure

While we will usually think of working agreements as dictated by the human to the autonomy, they can also be considered a negotiation between the two in which the human has the upper hand and final say. The autonomy may reject roles through considerations of an inability to perform a particular function, and/or due to current configuration. One could also allow agents to bid for particular tasks. While most often this pattern may have a strictly one way decision process, one can envision a two-way negotiated agreement fully deserving of that title.

Additionally, once a working agreement is set, its presence allows the human and autonomy to work as teammates rather than necessitating a strict supervisory control abstraction, if the agreement has been so specified.

Figure 4-9 uses a graphical language defined in Ref. [17] to illustrate the team structure being employed. In the figure, we see that the human and autonomy are teammates, both using a common collection of tools to perform work processes. While many implementations may look more supervisory in nature (which could be illustrated by a directional edge between human and autonomy) we diagrammed the more general case.

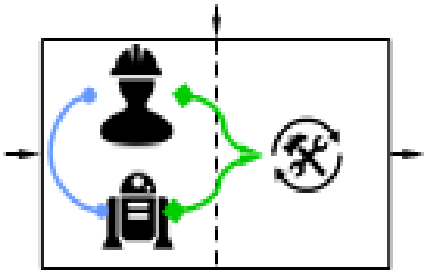

Figure 4-9: Working Agreements are at Their Most General a Teaming Relationship Between Human and Autonomy [69].

The working agreements themselves can be implemented with a variety of structures. However, the recommendation is to use a structure shown in the following figure.

In Figure 4-10, we show that an agreement is between two or more agents. Agreements are associated with tasks to be performed. In particular, we are interested in situations where a human is entering into an agreement with an autonomous artificially intelligent agent.

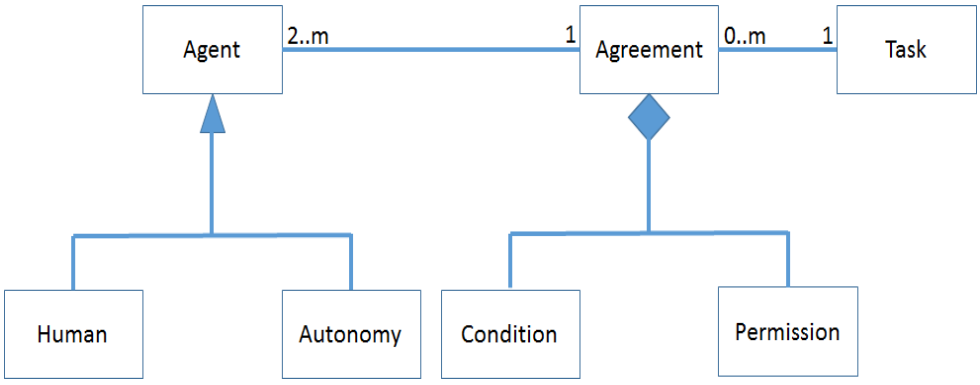

Figure 4-10: Working Agreement Structure Using Unified Modelling Language.

We use a task, method breakdown shown in Figure 4-11, for an unmanned systems command and control task allocation. Methods can be associated with agents and we can collect data about performance of agents for methods and tasks. Key to working agreements are the conditions under which each set of permissions is valid, and thus, whether the implementation is useful.

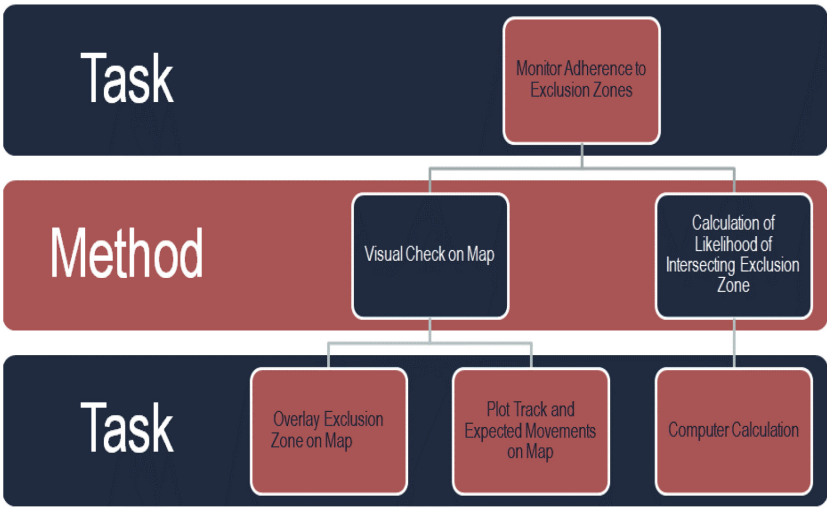

Figure 4-11: Example of Task-Method Breakdown [18].

4.4.7 Consequences

Working agreements are theorized to provide several values to human-autonomy partnerships. A few theories include that agreements should:

1) Improve teamwork through transparency, and roles clarification;
2) Provide a stable representation of the goals and limits of multiple partners in an environment, thereby lessening the burden on memory and training of the human user; and
3) Inspire the refinement and definition of tasks and conditions.

Better allocation will take advantage of differential skill sets between man and machine and take into account the information and understanding needed by a human teammate.

Evaluating working agreements is, in essence, about the assessment of the whole system of systems incorporated in the environment. Naturally, performance is a key parameter. However, additional conditions should be examined, and we consider a few of them here (though this is not an exhaustive list).

1) Whether there are emergent factors not captured by the task-methods hierarchy should be determined. Emergent factors could easily disrupt performance of the whole system or any of the parts; for example, user fatigue may disrupt whole system performance independent of any helpful effect of a working agreement.
2) To ensure each party's adherence to the agreement. If an agreement is violated, it might be important to understand the conditions surrounding the violation, but it also means the agreement was not actually in place.

3) A determination of agent comprehension of the agreement should be made. A user that does not understand the limitations imposed by an agreement will not act properly in the environment, so any performance consequences will not be the result of the agreement.
4) Assessments must ensure there was correct and timely recognition of any triggering elements, events, conditions, and contexts that might comprise the agreement itself. The need for recognition applies to all agents in the agreement.

In order to evaluate the result of a working agreement when it is functioning properly, we turn to the measurement of human-automation function allocation [70]. As agreements define function allocation schemes, once a set of requirements are met, they can be evaluated by a grouping of measures advocated by Pritchett et al., of which we deemed the following as crucial to working agreements:

1) Assessments of user workload, and taskloading. This measure may be facilitated by the specific task-based design and task-methods hierarchy breakdown. For example, certain task agreements may generate more or less demand on a human user, or create bandwidth overload on networked systems. There may be optimal agreements, then, that moderate workload and system performance.
2) A measure of authority as compared to a measure of responsibility. In other words, is there an imbalance between the controlling agent and the agent responsible? A working agreement, properly implemented, should directly improve this measure.
3) The stability of the performance and system environment, to the extent it is operationally relevant.
4) The measurement of interruptions, particularly interruption frequency and probability, as well as their effects on operator performance. For example, some function allocation schemes require repeated authorization or input from the human operator, sometimes to the detriment of their performance. Does a particular working agreement improve on, or make this situation worse?
5) The capabilities and limitations of automation and the behaviors that result when they are exceeded by the environment or the user. These may improve, to the extent they are captured in a working agreement, although this is unknown.
6) System cost and performance; is the working agreement improving either, as the result of its effective implementation?
7) How well does the human adapt to any context changes? Some working agreement settings may allow the user to exert more control or allocate more attention to tactics, for example, while others may mean the human is performing more menial labor.

We also suggest that measures of the human's trust in the autonomy may improve through increasing the transparency of function allocation.

Of course, one of the gaps identified here is that working agreements and human-autonomy teams in general have not been adjudicated by these measures. Working agreement assessment is a move toward requiring measures of function allocation, and experimental exploration of design.

4.4.8 Implementation

Working agreement employment will require determination of what tasks are present to be split between human and machine. This is a fundamental function allocation task, and has puzzled engineers of complex systems before. However, here and elsewhere we believe we have a good approach in the application of a task-method hierarchy [61].

We are using this method to determine tasks and methods within a multiple unmanned system command and control environment. Here, supervisory control may be shared between humans and autonomy, creating unique teams [48]. It required the definition of tasks (which were in part derived from subject matter experts), as well as determining the possible conditions surrounding whether automation was capable or should be allowed to perform them.

Working agreements should always be developed in conjunction with user-centered design practices and testing. No amount of a priori assumptions by designers will ever compensate for hands-on, iterative testing with actual users of a system. It is unlikely that all possible effects from all possible combinations of agreements can be understood before users attempt to interact with them. As the autonomy should be viewed as a teammate, the display of the working agreement conditions and status is key in informing the user about the agreement. Efforts should be made to make sure this display is user-friendly and unambiguous through usability assessment and experimentation [71].

It is also critical to ensure that interacting with the agreement occur before operations begin, allowing operators to orient themselves to the situation and conditions. Orientation, as it facilitates communication and coordination, is key to teaming. One could argue that by centering on tasks, a working agreement helps define the work for the team; doing so before work begins may be the most effective approach.

Conditions in which the agreement language itself is unclear may arise. Clarity should be a design goal and should be facilitated by the task-method basis for the agreements and by user-centered design. For example, in air traffic control, there are specific assignments and air space coverage areas that are referenced in agreements, which delineate “who does what” in a verbiage that all parties understand. In the Consequences section above, we discussed some ways to measure the effectiveness of working agreement implementation; these methods may also capture something like language ambiguity problems, whether it is reflected in user trust, particular agreement configuration patterns, workload, and stability.

Implementation may be limited to where there exist definable, separable tasks, roles, and responsibilities. While this will cover most forms of human-automation teaming at a high level, it will not cover others. A good example of something difficult is the automation present in fly-by-wire systems used in high-performance aircraft which smooth human operator input and maintain flight stability; since the “parts” are not separable it would be very difficult to split tasks out. A similar problem exists when examining basic control of robotic systems that use automation to control robotic arms with high degrees of freedom. In essence, it may be difficult to implement working agreements in automated systems that do not allow for some amount of part-task separation.

As noted elsewhere, separating tasks may have important implications for training [72], [73]. Part-task training methods characterize how many automated systems are created, with the automation taking some tasks out of the users’ hands. Naturally, the shift of “who does what” between operators and automation affects what users learn to perform [74]. Accordingly, the implementation of working agreements may help structure examinations of training with automation. Working agreements could be chosen and enforced experimentally, and measured along with training and skill acquisition of the users, to determine which agreements improve operations, and train the best skills for a given domain [74].

4.4.9 Negotiations

A critical aspect of creating working agreements is negotiation. While one can assume that the human dictates and the autonomy accepts, that is simply one type of negotiation.

4.4.9.1 Background and Notation

Previously, agreement patterns have been used in support of reusable software architectures, Peer to Peer (P2P) computing, service providers, etc. Patterns have also been identified in support of Human-Autonomy Teaming (HAT) [42]. Ref. [42] describes working agreements as large tasks that could be split into smaller tasks, the human works on one task and the autonomy works on the other thus working as a team. Ref. [42] also suggests that working agreements can be dictated by the human to the autonomy, but can also be considered a negotiation between the two in which the human has the upper hand and final say.

This section provides provision for a human conducting all or part of one side of a negotiation and the autonomy undertaking all or part of the other side of the negotiation from within a HAT context. However, the formalization of negotiations discussed in this section does not address the physical (hardware and software) implementation where context sensitive consideration needs to be given to when operator intervention is required and how this might be alerted. The Negotiation formalism is an implementation independent framework that that can be used to supports system design (as well as validation and verification).

In Ref. [75] agreement patterns are represented in three steps:

- Informal Representation;
- Reasoning Diagram; and
- Formal Representation.

Informal representation uses classifications to direct the description, a reasoning diagram to show the elements of the agreement, with the formal representation identifying the preconditions and postconditions for entering and concluding the agreement.

4.4.9.2 Informal Representation

Patterns can be represented as an informal representation, UML notation, pattern languages or ontologies. One type of informal representation for patterns can be given in canonical format [76] such as in Figure 4-12.

Within Figure 4-12 '*Phase*' can contain a variety of different elements in the description:

- **Provider selection:** Selection of the provider before entering an agreement negotiation.
- **Agreement negotiation**: Process of establishing the conditions of the agreement.
- **Agreement enactment**: Commitment that the agreement is effective.
- **Agreement renegotiation**: Phase of changing the conditions of a previously negotiated agreement.
- **Agreement monitoring**: Process of reviewing the established agreement conditions during the agreement enactment.
- **Agreement conclusion**: Process of concluding the agreement by any party.

4.4.9.3 Reasoning Diagram

The second step of pattern agreements is a reasoning diagram. The reasoning diagram represents the decision-making process for the agreement. We use The CommonKADS Methodology [77] as explained in Figure 4-13.

NAME: A meaningful name that provides a vocabulary for discussing, *e.g., EVACS, CloseAirSupport, AirspaceChange.*

DURATION: *Short term / long term / months / years, etc.*

CONTEXT: The preconditions under which the problem and its solution seem to recur, *e.g., ID needs confirmation before entering negotiation.*

FORCES: A description of the relevant forces and constraints and how they interact with one another and with the goals. Considerations to be taken into account to select a solution for a problem, *e.g., may run out of fuel, not enough time to complete task.*

SOLUTION: Static relationships and dynamic rules describing how to realize the desired outcome, *e.g., service provider selection is based on the rating given to service providers using reputation or trust techniques.*

EXAMPLES: One or more sample applications of the pattern which illustrate its application. Known occurrences of the pattern which help in verifying that the pattern is a proven solution to a recurring problem, *e.g., can be used in a policy manager.*

RESULTING CONTEXT: The state or configuration of the system after the pattern has been applied, *e.g., the UAV is now operating in Class A controlled airspace.*

PHASE: Provider selection, agreement negotiation, agreement enactment, agreement renegotiation, agreement monitoring, agreement conclusion.

RELATED PATTERNS: Compatible patterns which can be combined with the described pattern, *e.g., platform handover from maritime to air component may be the same as platform handover from air to maritime component.*

Figure 4-12: Informal Representation of a Pattern [75].

Figure 4-13: The CommonKADS Methodology Notations [77].

The Knowledge *role* describes the functional role of data on which the inference operates and describes. *Inference* describes functional roles such as abstract names of data that indicate their role in the reasoning process.

4.4.9.4 Formal Representation

The third part of the agreement pattern is to identify the preconditions of entering the agreement and postconditions of concluding the agreement from the context and resulting context respectively.

We can write the preconditions and postconditions both informally and formally. For example, see Table 4-3.

In the formal representation of Table 4-3 we denote *bat_life* to be the battery life of the platform in minutes and *plat_alt* to be the platform altitude in feet.

Table 4-3: Example of Preconditions and Postconditions of a Negotiation Written Informally and Formally.

Preconditions	Postconditions
Battery life on the platform has more than 10 minutes	Platform is flying at 1000 feet AMSL
bat_life > 10	*plat_alt = 1000*

4.4.9.5 Agreement Pattern for Negotiation

In this setting we define an agreement pattern to describe the situation where an Unmanned Air Vehicle (UAV) operator, or UAV autonomy, needs access to controlled airspace which it currently does not have authorization to enter. This is to conduct a task in accordance with its mission, for example if the UAV is following a track and to keep following the track the UAV needs to enter a new airspace zone.

4.4.9.6 Informal Representation of the Airspace Agreement Pattern

NAME: Auto Airspace change.

DURATION: Short Term.

CONTEXT: UAV operator/autonomy system needs access to airspace for which there is no current authorization (for example UAV is tracking a target that is heading outside of the search area currently allocated to the UAV which needs to relocate to maintain track).

FORCES: Pattern applicable when task requiring access to new airspace is within mission bounds (i.e., a new mission plan is not required), UAV operator/autonomy can handle any restrictions authorizer may give (e.g., area/height/time bounds), there is an identified authorizer (e.g., Air Battlespace Manager) and there are no other known circumstances which negate the validity of the request (e.g., emergency recovery plan invalidated due to insufficient fuel).

SOLUTION: Approver authorizes the request, if there are restrictions with the approval then the UAV operator/autonomy must confirm compliance with these restrictions before entering the airspace.

EXAMPLES: Policy Management.

RESULTING CONTEXT: UAV is authorized to enter the airspace to conduct task.

PHASE: Agreement negotiation, Agreement enactment, Agreement renegotiation, Agreement conclusion\\.

RELATED PATTERNS: None.

Figure 4-14: Informal Representation of the Airspace Agreement Pattern

4.4.9.7 Reasoning Diagram of the Airspace Agreement Pattern

The reasoning process (Figure 4-15) commences when there is recognition that the platform requires access to some airspace. (this is a knowledge role). The platform then needs to assess the mission bounds. A mission bound could be that by entering this airspace the Emergency Recovery Plans and overall time/endurance are not adversely affected. Since assessing conformance with mission bounds needs more information this becomes an inference role. The approver then needs to respond to the platform's request, the approver in this case being the airspace controller. Their response can be either:

1) Allowing the platform to enter the airspace;
2) Not allowing the platform to enter the airspace; or
3) Allowing the platform to enter the airspace with restrictions.

The restrictions can be a list of things such as duration, height, part of the airspace requested, etc. The platform operator/autonomy then assesses the approver's response and decides if it can handle the restrictions and, if compliant, enters the airspace. Since there is some calculation in the assessment part of the reasoning diagram this becomes and inference role. After assessing the response, the platform then decides if it will enter the airspace or not.

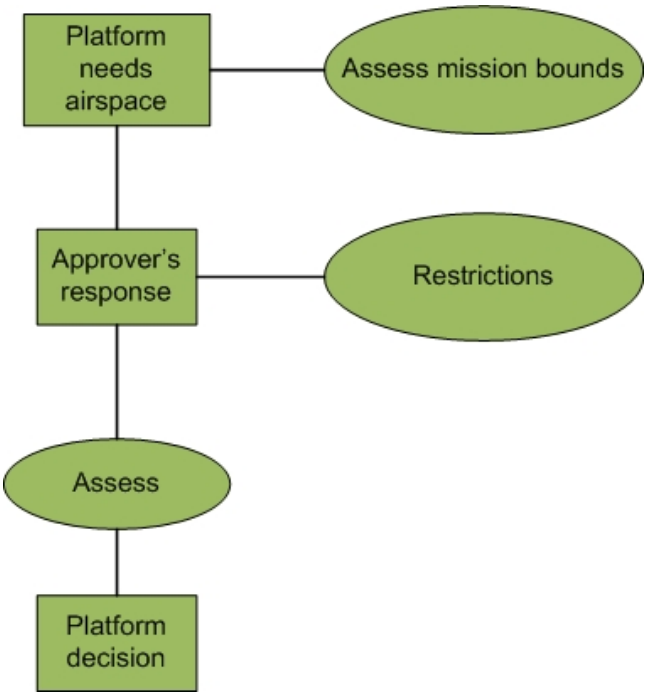

Figure 4-15: Reasoning Diagram for the Auto Airspace Change Negotiation.

4.4.9.8 Formalizing the Airspace Agreement Pattern

The third part to the agreement pattern is to identify the preconditions of entering the agreement and postconditions of concluding the agreement. We can identify these preconditions and postconditions in our airspace (see Table 4-4).

Table 4-4: Preconditions and Postconditions in Airspace.

Preconditions	Postconditions
UAV is flying in its allocated airspace UAV can handle restrictions	UAV enters newly allocated airspace

To formally define the two preconditions and one postcondition we have defined for the airspace changing task we need to have the following variables and their types. See Table 4-5.

Table 4-5:Variables and Types Required Defining Preconditions and Postconditions of Airspace Changing Task.

Variables and Types	Details
ap: ACTOR	ap is the approver
*approved: (ACTOR1 * ACTOR2)*	approved is a set of pairs which takes two actors meaning ACTOR1 is approved by ACTOR2
m: ACTOR	m is the mission bounds
*flying: (ACTOR1 * AIRSPACE1)*	flying is a set of pairs which takes two actors meaning ACTOR1 is flying in AIRSPACE1
u: ACTOR	u is the UAV
a1: AIRSPACE	a1 is the airspace the UAV is allowed to fly in
a2: AIRSPACE	a2 is the airspace the UAV is trying to get into
res: ACTOR → P PARAMETERS	res is a function which takes an actor and outputs a set of parameters (or restrictions)

The first precondition we wish to represent formally describes that before the platform even wants to enter its new airspace, it is flying in some kind of airspace already. Therefore, we have the following:

$$flying\ (u, a_1) \wedge (\neg\ flying\ (u, a_2))$$

This statement represents that the platform, in this case UAV *u* is *flying* in airspace1 a_1 **and** the UAV *u* is **not** *flying* in airspace2 a_2.

Another precondition we wish to identify before entering the negotiation is that the UAV has some restriction it will be able to handle if the approver gives any. We write this as the following:

$$res \sim u \neq \{\}$$

This statement, the variable *res* takes an actor as an argument, in this case we have the UAV. Therefore, the first part of the equation "*res ~ u"* represents the set of restrictions *res* which the UAV *u* can handle. The second part "$\neq \{\}$" represents that the set is **not** empty. Therefore, the UAV has to have at least some restrictions which it is able to handle. At this abstract level of representation, we do not actually care what the restrictions are, just that they exist.

The next part we wish to represent is the postconditions of the negotiation and the outcomes.

We will represent the postconditions as follows:

$$flying\ (u, a_2) \wedge (\neg\ flying\ (u, a_1))$$

This statement shows that now after the agreement, the UAV (u) is flying in airspace2 (a_2) and the UAV (u) is not flying in airspace1 (a_1). This is the reverse to the first formal statement we produced where the UAV was flying in airspace1.

4.4.9.9 Benefits

By using agreement patterns, we can identify a common framework to exchange procedures and protocols between various services. We concentrate on three key points of why agreement patterns for negotiations are beneficial:

- Common Framework – similarities and differences identified;
- Step towards automation; and
- Reduce ambiguity in system requirements.

Some patterns of negotiations may be similar to each other e.g., handing over aircraft from a land to maritime component may be similar / the same / completely different to handing over aircraft from maritime to land. Comparisons such as these can be made more easily if the negotiations and policies in which they lie are represented as agreement patterns. Not only can a comparison be made across the different negotiations but a common framework will make it easier to spot the similarities and differences across the different services as well.

Agreement patterns for negotiations can support negotiations that are conducted automatically to resolve conflicts. In our example, the negotiation for new airspace is usually undertaken between a UAV operator and the relevant airspace controller. However, by representing the negotiation as an agreement pattern, it becomes a step towards an automatic negotiation i.e., UAV autonomy, either at the platform or the control station, can ask the airspace controller for airspace access once it recognizes that it is needed. Such functionality supports supervisory control of UAVs by operators that might be undertaking task-level control of a platform, or operators that are exercising supervisory control of multiple platforms and therefore seek automation of such routine tasks whenever appropriate in order to manage workload.

There may also be similar elements across different negotiations such as track handover and Close Air Support (CAS) 9-Line tasking. Negotiations as pattern agreements can be shared and reused for other procedures which may arise in future. Formal agreement patterns help the definition of user requirements and functional specification and should software design preserve the structure of the pattern agreement this can facilitate or support software validation and verification.

By identifying the preconditions and postconditions, one can highlight which conditions need to be satisfied in order for correct negotiation. The formalization can help capture exceptions and errors e.g., if precondition is not met then send alert message, abort, etc. Formalizing preconditions and postconditions could also support other machine reasoning techniques such as temporal logic, fuzzy logic, etc., as well as reducing ambiguity in the system design, helping precise description to all stakeholders.

4.4.10 Commitments

In addition to negotiation, commitment is a critical aspect of the creation, fulfillment and closing of working agreements. Singh's commitment model [78] has been used to build a Work Agreement (WA) framework, which makes software socially adaptive and defines human values in such a way that possible commitment conflicts can be resolved automatically [79]. In this WA-framework, a *debtor* agent is committed toward a *creditor* agent to effectuate a consequent if a specific antecedent is present.

Similar to the negotiation-based agreements, a general interaction design pattern has been constructed for the commitment-based specification, activation, monitoring and closing of agreements (Figure 4-16) (for details see Ref. [80]).

NAME: Obtain adjustable human-agent working agreements on object handling.

DURATION: Short Term.

CONTEXT: The information that the team has to process for object handling is highly dynamic, causing high peaks and deep hollows in workload, the agent can perform "only" well-delineated information processing tasks adequately, and the human operator should remain in the loop (1) to maintain the Situation Awareness for adequate performance of the complex or unsteady tasks, (2) to assess the work strategy, and (3) to maintain overall responsibility.

FORCES: When a clear-cut part of the work can be automated and humans are needed (a) to deal with the uncertain or ill-defined information, and (b) to take the overall responsibility for the information processing strategy and outcome.

SOLUTION: The human operator (as "Creditor"), sets (1) the delegation criteria (e.g., the area of operation and characteristics of possible objects in this area that the agent is obliged to handle) and (2) the corresponding handling tasks (e.g., identify and monitor). The agent will meet this social commitment and act according to the defined settings with the corresponding obligations, i.e., as "Debtor", show the task outcomes with the conditions that led to these outcomes (e.g., sensed attributes of an object).

EXAMPLES: A prototype of a "track handling agent" for a naval operator was developed [57] and tested [81].

RESULTING CONTEXT: Adequate Situation Awareness, appropriate work strategy and responsibility awareness.

PHASE: Agreement Negotiation, Agreement Enactment, Agreement Renegotiation, Agreement Monitoring, Agreement Conclusion.

RELATED PATTERNS: See Ref. [80], [82] (e.g., Tailored Situation View).

Figure 4-16: General Interaction Design Pattern Has Been Constructed for the Commitment-Based Specification, Activation, Monitoring and Closing of Agreements

An ontology has been developed that defines the core concepts of the WA-framework with their relations, comprising the knowledge to specify, activate, monitor, and reason about work agreements: <creditor, debtor, antecedent, consequent, lifespan, acceptance>. This framework, with its ontology, was implemented and tested for human-robot teams in disaster response (i.e., the TRADR-project). These team need the capability to dynamically adapt the task allocation and coordination to the momentary context. Field tests with actual robot-assisted disaster response teams, showed that the fire-brigade officers could specify work agreements as required, which, subsequently, brought forward the desired adaptive team behavior of the concerning robot.

Team design patterns specify generic reusable behaviors of actors for supporting effective and resilient teamwork. These patterns can be used to describe the dynamics of teamwork over longer periods of time. They can be constructive (i.e., leading to a more coherent team) or destructive (i.e., leading to a less coherent team), which can be observed in the behavior of an individual or group of actors [82]. During a field test, for example, the TRADR team showed an individual, destructive micro-management pattern of the team-leader. By defining and implementing a work agreement, this type of destructive behaviors cab be prevented in future situations.

4.4.11 Known Uses and Related Patterns

The domain of Air Traffic Control (ATC), which depends on proper coordination of aircraft flight paths between multiple human controllers for the duration of a flight, has historically used a working agreement model. The official term is letter of agreement, and they are employed by both the Federal Aviation Administration and by European Organisation for the Safety of Air Navigation (EuroControl) [83]. Letters of agreement follow a standard format to supplement procedures that address the needs of particular sectors of airspace. In two ways, these agreements are adhering to our earlier principles for working agreements:

1) That language has to be clearly understood by the parties involved; and
2) That agreements foster the articulation of tasks to enable themselves.

The domain of disaster response also shows the formalization of working agreements, to attune the division of tasks and responsibilities to the context of operation within the normative constraints (e.g., on safety, health and humanity).

While letters of agreement can cover a variety of scenarios, in general they serve to:

a) Define responsibilities and coordination requirements;

b) Establish or standardize operating methods;

c) Specify special operating conditions or specific ATC procedures; or

d) Delegate responsibility for an ATC service [84].

These letters of agreement are negotiated by the parties involved, which for ATC could mean two airspace sectors, but also between entities, such as between the Los Angeles Air Route Traffic Control Center and Tijuana Terminal Radar Approach Control (Figure 4-17) [85].

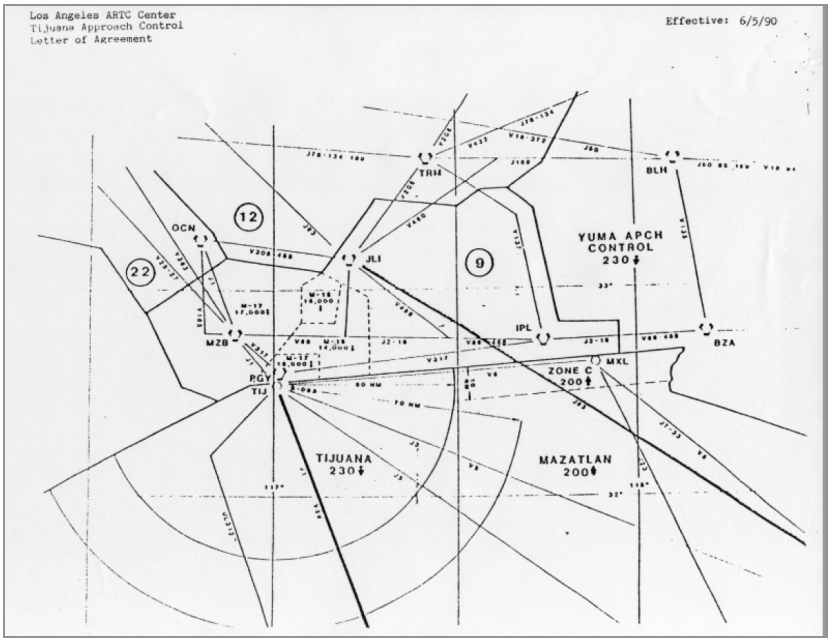

Figure 4-17: Airspace Description of the Letter of Agreement Described in Ref. [85].

In either case, the agreements define the purpose, scope, responsibilities, and procedure for both parties. Henceforth, parties are equipped with the necessary awareness to coordinate, delegate, and safely proceed with shared ATC procedures.

Air traffic controllers are familiar with these agreements between sectors of airspace, and are trained to split tasks within the same sector. A good example of this behavior is within teams assigned to some En Route sectors, who split work between a primary Radar position (R-side) and a secondary Radar Associate operator (D-side). The Associate supports the R-side operator by taking over housekeeping tasks, such as aircraft handoffs and assisting in separation assurance [86].

Effective teaming and negotiation of the agreement helps define a task allocation schema. In this schema, the D-side acts as a collaborator to help solve difficult conflicts. Much like a working agreement, each team must uniquely determine task allocation and conflict resolution strategies (such as a preference for issuing orders to aircraft to change vector, vs. directing them to change altitude, in order to avoid collisions). Close collaboration and transparency between an R-side and D-side is critical, as not all of these agreements are formal.

As the push toward automation of the national airspace gains momentum, the D-side operation is a natural candidate for supportive automation. With automation systems, the agreements would need to be made formal to enable teamwork. The NASA Ames Airspace Operation Laboratory has been investigating the allocation of tasks between a human air traffic controller and ground-based separation assurance automation since 2008 [87]. These experiments specifically target increasing the total number of aircraft in a sector at any given time, while maintaining safety. Several experiments yielded confidence that separation assurance automation is a viable candidate for mediating workload in future, denser airspaces [87]. However, the relationship between the R-side air traffic controller (human) and automation for the D-side is still under investigation.

A 2010 experiment highlighted the human's willingness to delegate housekeeping tasks to the automation [87] One notable finding was that controllers preferred authority over decision-making tasks, such as approving weather reroutes. However, the majority of controllers indicated post-study that they would still share tasks with the automation, instead of completing them in isolation. This collaboration paradigm mimics the current R-/D-side collaboration between human controllers. It also suggests that in formulating working agreements, whether or not the task-element contains decision-making points may influence whether an operator will trust that element in the agreement.

Transparency and goal alignment are critical in human-machine teaming. More focused analyses of the data from the 2010 study offered additional insights. Operators have specific preferences in conflict resolution (which the automation in the study did not take into account). Controllers often wanted a different type of conflict resolution than the automation could provide. The automation went about resolving conflicts in a very different manner [88] which violated controller expectancies.

Unlike a human D-side who could be told a specific way to do a task, or at least could be negotiated with, controllers had to work around the limitations of the automation. Controllers were given no insight or interface for delegating tasks or the methods used to perform them. Implementing working agreements specifically would allow the users to articulate how they want to limit or expand the behavior of the automation, solving some of these problems, and building toward improved human-machine teaming.

4.4.12 Conclusion

In this section we have discussed agreement patterns as applied to negotiations and commitments within a military domain. These negotiations are represented in three different ways, informal, within a reasoning

diagram and formalized with preconditions and postconditions. Each step can describe the negotiation in a different state and thus be understood by a variety of audiences. By giving a high-level overview of these negotiations, they can be generalized and applied to a mixture of scenarios. Repeated negotiations that are required by applicable procedures and policies, and which have to be performed to complete certain tasks can be represented as agreement patterns. Instead of human operators conducting negotiations repeatedly, the autonomy within a system can, when and where appropriate, do this on the operator's behalf and therefore enabling higher levels of supervisory control by human operators in situations where this is desirable.

The agreement patterns we have described here are mainly focused on negotiations and commitments between an autonomous agent and a human (UAV and airspace manager; or UxV and rescuer), supporting human-autonomy teaming where autonomy is giving the human information, and is asking for permission to complete a task. Other examples of negotiations between human and machine could be when handing over a track from one platform to another, handing over a platform from one user or controller to another or calling for a platform to undertake a specific task such as CAS or Casualty Evacuation (CASEVAC) 9-Line tasking requests.

By evolving from human-human negotiations through human-autonomy negotiations and applying appropriate policy management for control of autonomy, implementation independent formalisms for future autonomy-autonomy negotiations can be matured that provide both trust and transparency to operators, as well as providing progressive safety evidence to regulatory authorities.

4.5 POTENTIAL SOLUTION 3: TRANSPARENCY

4.5.1 Intent

The goal of the Transparency Pattern is to provide a general human-machine interface design solution to support human-agent communications in order to achieve joint decision-making effectiveness. Design patterns are reusable solutions that can be used for various interface designs. More specifically, the pattern describes the information requirement from the agent to support the human's awareness of the agent's:

1) Current actions and plans;
2) Reasoning process; and
3) Outcome predictions.

We discuss general design patterns related to the Situation Awareness-Based Agent Transparency (SAT) model that aided in the development of transparency designs for the Intelligent Multi-UxV Planner with Adaptive Collaborative/Control Technologies (IMPACT) project funded by the US Department of Defense's Autonomy Research Pilot Initiative (ARPI) [89], [90].

4.5.2 Motivation

As autonomous systems become more intelligent and more capable of complex decision making, it becomes increasingly difficult for humans to understand the reasoning process behind the system's output [91]. However, such understanding is crucial for both parties to collaborate effectively, particularly in dynamic environments [92]. Indeed, *Explainable AI* [93], a DARPA program announced in August 2016, underscores the importance of making intelligent systems more understandable to the human. The US Defense Science Board recently published a report, *Summer Study on Autonomy*, in which the Board identified six barriers to human trust in

autonomous systems, with 'low observability, predictability, directability, and auditability' as well as 'low mutual understanding of common goals' being among the key issues (see Ref. [94], p. 15).

Lee and See [95] identified three components of an agent whose transparency influences operators' trust calibration: purpose, process, and performance (3Ps). Lee [96] proposed that to increase transparency in machine agents, the system's 3Ps and performance history should be displayed to the operator in a simplified form (e.g., integrated graphical displays) so the operator is not overwhelmed by too much information [97], [98]. Chen and associates [99] leveraged Endsley's model of Situation Awareness (SA; [100]), the Beliefs, Desires, Intentions (BDI) Agent Framework [101], Lee's 3Ps described above [96], and other relevant previous work [92], [102] to develop the *Situation Awareness-Based Agent Transparency* (SAT) model (Figure 4-18). Drawing inspiration from Endsley's [100] three levels of SA – perception, comprehension, and projection – the SAT model describes the information that agents need to convey about their decision-making process in order to facilitate the shared understanding required to perform effective human-agent teamwork [99], [103]. While SA is the cumulative result of three hierarchical phases, the SAT model is comprised of three independent levels, each of which describe the information an agent needs to convey in order to maintain a transparent interaction with the human [99], [100].

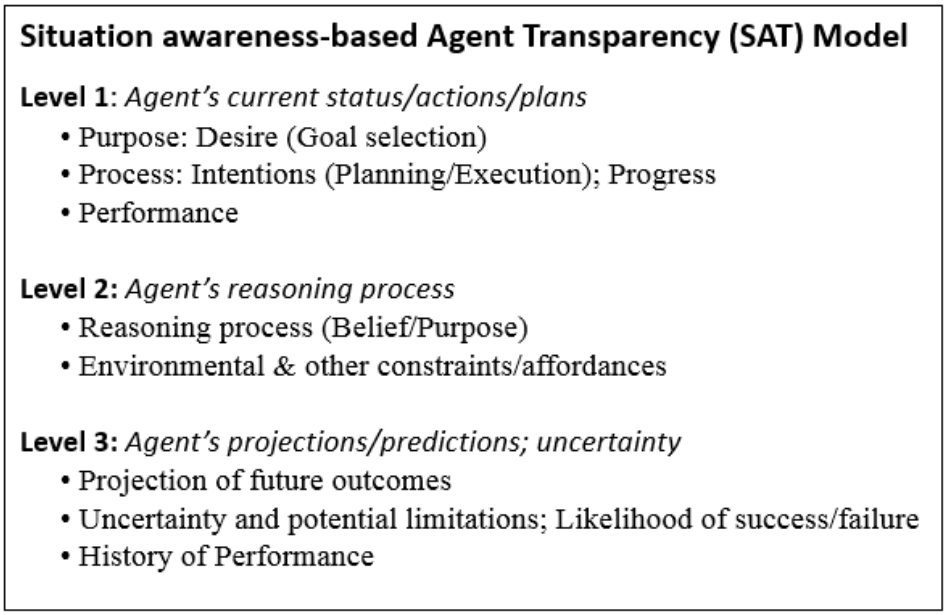

Figure 4-18: Situation Awareness-Based Agent Transparency (SAT) Model.

4.5.3 Applicability

The Transparency Pattern based on the SAT model can be applied to a wide variety of human-machine interfaces, where the agent's reasoning information and projections of future outcomes (including uncertainty) are important to its/his/her team members (humans or machines). This pattern was applied to the design of the Transparency Module of the human-machine interface for the Intelligent Multi-UxV Planner with Adaptive Collaborative/Control Technologies (IMPACT) project funded by the US Department of Defense's Autonomy Research Pilot Initiative [89], [90]. This project involves the use of an agent that manages multiple unmanned vehicles in a military mission environment using a 'play-calling' paradigm [104].

4.5.4 Structure

Figure 4-19 is an example of the Transparency Pattern adapted for the IMPACT program. The chief feature is the interaction of three intelligent agents (route planner, asset manager and plan monitor) to help plan a mission and dynamically re-plan as the mission monitor notes deviations from the original plan and coordinates with asset manager and route planner for the suggested new plan. In this instantiation, the asset manager is enabled to supply the operator with the new plan's intent, logic and expected outcomes. The operator, based on the transparency information, can decide whether to accept the suggested plan or an alternate plan (perhaps a pre-designated solution or "play").

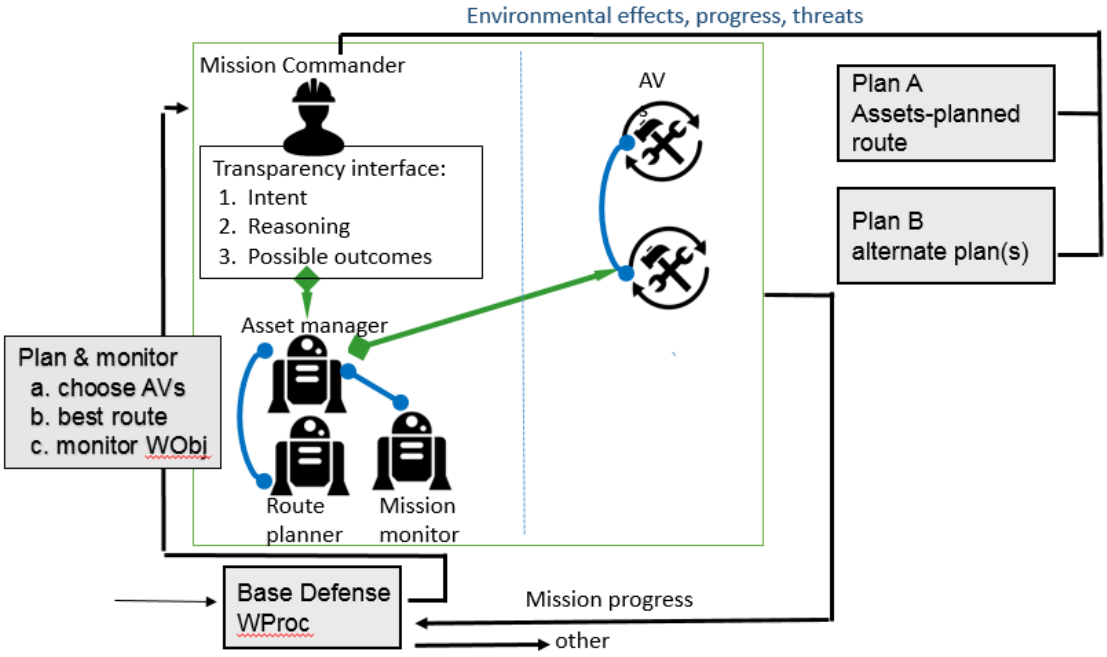

Figure 4-19: Transparency Pattern Based on the SAT Model.

4.5.5 Participants

The participants shown in Figure 4-19 are:

1) Human Mission Commander (MC) who is final arbitrator of the mission plans that include the type of autonomous assets (ground, aerial and sea surface) to send to the reported trouble area, the best route to do so, and changes during mission execution (e.g., "send additional assists"). He or she can accept the plan from the agents, ask for additional options, or create a manual plan. The MC also starts the process by passing parameters defining the criteria the agent will use to complete the planning process.
2) AVs (autonomous vehicles) follow the plan that the asset manager directs (with the MC having final decision authority) but are not controlled by a human operator.
3) Three collaborating intelligent software systems (Asset Manager (AM), Route Planner (RP) and Mission Monitor (MM)) each with it is own speciality that enables agents to jointly plan and re-plan the mission.

4) The SA-Based Agent Transparency (SAT) interface is the communication medium between the agents and the human. The interface, based on the agent's (AM) output, displays the plan or revised plan and their intent, reason for choosing the plan, and its expected outcomes (including any uncertainties, e.g., weather). The SAT interface also shows comparisons among options (option A is the quickest plan to surveil the reported incident but option B has the better sensors) using graphical and text formats (see Section 4.5.9). The SAT interface also allows for bi-directional communication between the AM and the MC [99].

4.5.6 Collaborations

The agents collaborate to devise the best plan(s) based on inputs from the MC. The AM, using Pareto optimality, chooses the best available asset options based on MC inputs (possible plans (*plays*) and instructions). The RP uses algorithms to find the best route based on the AM instructions, iterating until the RP and AM converge on a common solution. If the MM notes deviation from the plan during execution, it starts the re-planning which reiterates through a further AM and RP collaboration based on the MM inputs. No plans are executed until the MC assents to them or the MC makes alternative plans.

The AM is the final repository of plans (and options). It uses this information to interact directly with MC through the SAT interface. The AM derives the SAT information based on the collaborative results not only for the favoured plan but also for other *possible* options. The interaction is bi-directional [99] permitting the AM to reiterate the planning process based on MC inputs ("what if we used ground vehicles?") and displaying the results on the SAT interface (comparing current plan to new plan).

4.5.7 Consequences and Justification

Experimental results (see Section 5.9 US-3 Agent Transparency for details) demonstrate that the SAT model provides a useful framework for organizing the information requirements related to agent transparency. More specifically, the results collectively suggest that transparency on the part of the agent benefits the human's decision making and thus overall human-agent team performance [105]. The human's trust in the agent was significantly better calibrated (i.e., accepting the agent's plan when it is correct and rejecting it when it is incorrect) when the agent had a higher level of transparency. As is found in human-human teams, communication of relevant information can facilitate processing and decision making by aiding in the creation of a shared mental model between team members [92]. The pattern demonstrates that interaction between a human and multiple intelligent agents can be modulated through an interface that permits bi-directional SAT graphic and text displays.

4.5.8 Implementation

The experiments based on the Transparency Pattern resulted in numerous conference papers and two journal articles [99], [106] and serves as the basis for further research on agent transparency interface in various military contexts.

The Transparency Pattern has been successfully applied to the design of the Transparency Module of the human-machine interface for the IMPACT project [89], [90]. The following section provides more details of the implementation efforts.

4.5.9 Examples and Known Uses

As part of the IMPACT effort, and to explore the SAT model's utility for UxV management, the SAT model served as a guideline in the design of two separate Intelligent Agent (IA) interfaces [105], [106]; Figure 4-20 and

Figure 4-21). These interfaces were adapted from the US Air Force Research Laboratory-developed IMPACT/Fusion interface [89], [107], and were further developed to convey SAT-based information. The designs used in Stowers et al. [105] are described below in details.

Figure 4-20: Interface 1: Displaying Information According to the SAT Model.

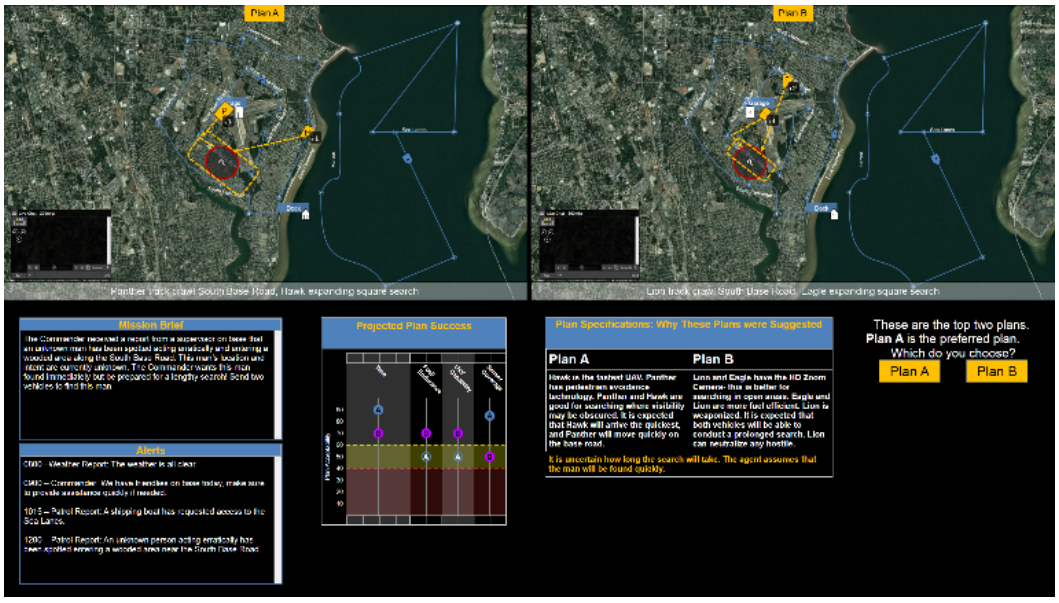

Figure 4-21: Interface 2: Displaying Information According to the SAT Model.

The IMPACT testbed and its human-machine interface are modular in nature, allowing the display of the IA's status and plans, reasoning, and projection in a scalable and ecologically valid way. Careful consideration led to the final inclusion of three key modules or tiles in the display: A *Plan Maps* tile, a *Projected Plan Success* tile, and a *Plan Specifications* tile (Figure 4-21).

Plan Maps. The interface presents two maps, one for each plan the IA suggests to the operator. SAT Level 1 information includes the IA's recommended plans and information about the UxV associated with these plans. SAT Level 2 information (reasoning) was displayed by the size of UxVs, with larger UxVs being faster. SAT Level 3-Projection information was displayed as an icon attached to each UxV to depict the number of time units it was from its goal location. SAT Level 3-Uncertainty information was displayed through changes in opacity of the UxVs themselves, where less-opaque vehicles were considered to have uncertain capabilities or time projections.

Projected Plan Success. The plan comparison tool, based on a design developed by US Air Force researchers [89], adds additional SAT Levels 2 and 3 information. This graphic shows the evaluation of both plans (A and B) on four different parameters: time, coverage, fuel endurance, and general capability. Circles representing each plan slide up and down scales corresponding to each parameter. Plan acceptability is rated on this sliding scale; the higher a circle is on the scale, the more acceptable the plan is for meeting that parameter. Level 2 information is conveyed through showing how heavily the IA is weighing each parameter as a representation of the IA's recommended plan and reasoning. This is done by ordering the parameters from left to right, with decreasing widths for less important ones. Level 3-Projection information is conveyed by showing the projected plan success of each plan for all four parameters. Finally, SAT Level 3-Uncertainty was represented with hollow circles instead of filled ones.

Plan Specifications. The Plan Specifications tile provides further information on the *Plan Maps* and *Projected Plan Success* tiles. For example, a detailed explanation of the reasoning process (constraints and/or affordances considered by the IA); projection statements to indicate the predicted outcomes of the plans; uncertainty statements specifying: 1) The IA was uncertain about certain aspects of the tasking environment; and 2) The IA was making an assumption to deal with it.

4.5.10 Related Patterns

The important advantage to using design patterns is that they can be adapted to inform multiple instantiations where human and agents interact, and the Transparency Pattern can be reused in contexts where information about the agents' reasoning process and projections/uncertainty is critical to human-agent team performance. The SAT pattern has been used to develop and evaluate transparency displays for the Autonomous Squad Member (ASM) ARPI program and design information requirements for ARL's Human-Robot Interaction research [99]. More details about the experimental results are available in Section 5.9 (US-3 Agent Transparency).

4.6 POTENTIAL SOLUTION 4: EXPLICIT INTENT COMMUNICATION

4.6.1 Overview and Scope

This section describes a candidate Human-Automation Teaming (HAT) pattern – Explicit Intent Communication – and offers a description of both the problem type(s) for which it is believed to be appropriate and the attributes of its implementation. Explicit Intent Communication is an approach addressing aspects of the type of information to include and suppress in HAT.

4.6.2 Intent

The goal of the Explicit Intent Communication pattern is to make intent an explicit, viewable, negotiable phenomenon/object between human and automation. This can apply to human intent, automation intent and shared intent.

4.6.3 Motivation

Misalignment, misunderstanding, lack of trust and inappropriate usage decisions are pervasive and well-documented in human-automation interaction. Making intent "viewable" – that is explicit and shared in the context of work – is a (probably partial) solution that has improved performance in human teams (e.g., in Cockpit Resource Management and in explicit, documented Commander's Intent statements) as well as, at least occasionally, in human-automation teams [38], [108], [109], [110]. A further step – making intent negotiable – adds more control and coordination possibilities (as well as, probably, awareness) but with costs and applicability conditions of its own.

4.6.4 Applicability

This solution has limits. Intents, like plans, are hierarchical and not all intents at all levels of decomposition are equally interesting or important. Furthermore, humans (at least) will have constraints on time and attentional capacity available to process, absorb and maintain awareness of the intent of co-workers – and there are contexts in which such time and attention will be further constrained. This is even more true of negotiation about intent. There are also conditions in which humans (at least) may not have well-formed intentions (as Klein has demonstrated in Recognition-Primed Decision Making [111]) and/or may be unwilling to declare them (such as a willingness to sacrifice troops under one's command).

As alluded to above, making intent explicit will *not* be applicable in conditions where the human has no time, interest, ability (due to time, attention or perhaps education/training) to understand or adapt to the automation's declared intent. Intent negotiation will *not* be applicable in conditions where there is no time or ability to modify the automation's intent or where modification (including overriding and shutting down) the machine intent is not advisable due to costs, dangers, inaccessibility, etc.

4.6.5 Structure

Figure 4-22 shows the proposed Explicit Intent Communication pattern using the notation originally provided by Schulte, Donath and Lange [17] using some of the modifications suggested by Miller [112]. One of Miller's proposed modifications is to provide both a problem pattern and a solution pattern. The problem pattern is a description of the "competing forces" [2] which, collectively, represent a context in which this solution pattern is useful or relevant, along with a notation (the arrows) representing a rough approximation of the weight or importance of those forces. The left-hand side of Figure 4-22 conveys that the "Explicit Intent Presentation" pattern will be useful in contexts where there is strong need for coordination and accurate trust tuning among human and automation workers, as well as traditional automation and tools in the work domain, and where the actors have some time and attentional capacity to devote to viewing explicit intent presentations, where the human has well-formed intentions and is willing to articulate them and has an ability to understand the intent conveyed by other elements of the system.

The solution pattern on the right side of Figure 4-22 shows that one or more human and/or advanced automation agents are in a hierarchical relationship with one or more traditional automation agents and tools. Relationships

among agents in both groups may be either hierarchical or heterarchical, but there should be a hierarchical relationship between the two groups.

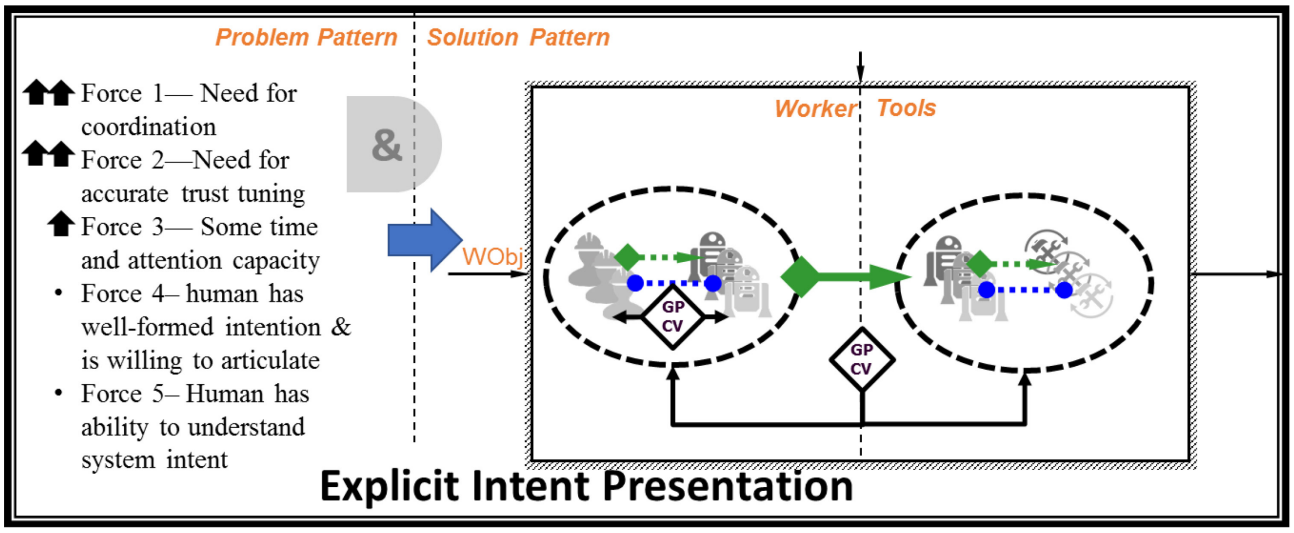

Figure 4-22: Pattern for Explicit Intent Presentation Illustrating Both Problem and Solution Characteristics.

Thus far, this is the "basic" supervisory control relationship from Miller [112]. The addition is the linking black arrows with the diamond in the middle. The diamond and letters "GPCV" were proposed in Miller, 2016, as a means of conveying whether delegation could be performed using Goals (G), Plans (P), Constraints/Stipulations (C), and/or Values (V). The presence of the black diamond here is meant to convey that all of these methods can be used in explicit communication between both Worker and Tool entities.

That representation seems a bit vague and ad hoc, however, so I also attempted a UML-based Use Case representation, in Figure 4-23. This conveys, a bit more concretely, that there is a core system or functionality in place labelled Intent Communication System which enables four use cases:

1) Issuing one's own intent (for one's self)[1];
2) Commanding intent for what another should do;
3) Viewing the intent of another actor; and
4) Approving and/or revising the intent of another actor.

Of these four use cases, humans should (generally?) be able to perform all four – though (as alluded to above) there may be circumstances where approving/revising automation or tool action cannot practically be permitted in the immediate context (hence the dashed line connecting human worker and the approve/revise use case in Figure 4-23). Advanced automation Workers should also be able to perform all four use cases, though their access to the Command Intent and Approve/Revise use cases may be restricted in some contexts. On the other

[1] The notion that traditional automation and tools have "intent" may be problematic to some since this may imply consciousness. I am happy to concede that they do not initiate intent in the same way that humans and advanced automation do, but I'd argue that they can "have" intent by having it assigned to them (and acknowledging it and acting to fulfill it – including subordinate decisions about methods to be used to achieve that fulfillment).

hand, traditional automation and other Tools have access only to the Issue Own Intent and Receive/Review Other's Intent use cases.

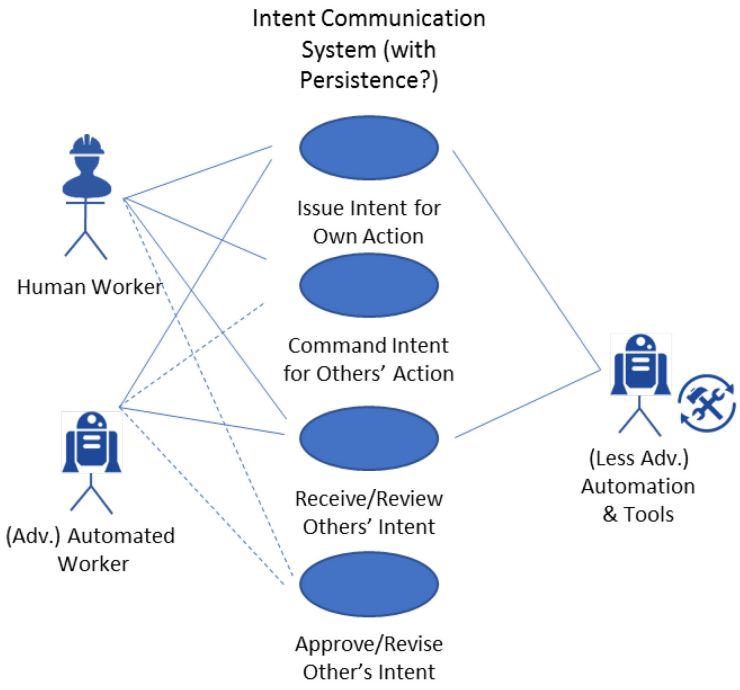

Figure 4-23: UML Use Case Representation for the Explicit Intent Communication Pattern (Illustrating Four Possible Use Cases).

4.6.6 Participants

The participants in this pattern are illustrated in Figure 4-23. They consist of one or more human workers and/or one or more advanced autonomous agents who, collectively, interact with one or more traditional Tools (including traditional automation) to perform work. Humans and autonomous agents may be in any pattern of hierarchical or heterarchical relationships and may have collaborative or independent (but not competing) goals.

The nature of the "Intent Communications System" is also significant. Intent communication can be effortful and time consuming or as simple as pressing a button. It can be flexible and highly expressive or limited to as few as two alternate behavioral states (including, in the most reductive case, on and off for a single behavior the automation is capable of). It can also be persistent (as in a long-term record of a declared intent which is visible and/or checkable at need), or it can be transitory (as most verbal communications will be). These variations will color the capabilities and requirements from the various agents in the instantiation of the pattern.

4.6.7 Collaborations

- When the Worker is a human, he/she will have greater need for visible, explicit and probably persistent information about the intent of subordinate and collaborative autonomous agents, automation and tools. Intent declaring Autonomous Agents will still need explicit information about the intent of others, but may not need it to be persistent.

- When intent communication is difficult or time consuming, this will increase the time and workload demands of reporting one's own intent and in issuing commands to others. This "coordination time" must be considered in design and operational planning – and may, in fact, make this pattern non-viable for some contexts.
- When significant uncertainty exists, either in the environment or in the performance capabilities of the automation and tools, the ability to review and assert influence over the performance of other agents will have increased desirability.
- The competence of Workers (whether human or automation) to both understand and report their own intent and, more seriously, to review and approve/revise others via intent statements, is not guaranteed. This mandates a design decision and perhaps an operating policy about which intents are to be declared, and which are available to be commanded and/or revised. It is frequently possible, though, to shift the act of reviewing and revising an intent from real time (i.e., seconds prior to execution) to non-real time (e.g., pre-mission).

4.6.8 Consequences and Justification

Using this pattern will increase the workload and information processing burden of those who perform both intent reporting and receive, review and reason about the intent of other agents in the system/team. If this effort exceeds the agent's capacity, then other tasks will be performed less well or dropped – and this information will have been a distraction.

On the other hand, if the information is successfully processed and understood, then greater situation awareness and, generally, better coordination will ensue from all members of the team. Furthermore, the fact of having an explicit declaration of intent available provides the opportunity to review and interpret the actions of others. This can facilitate trust tuning (by providing insight into an agent's "cognition" – that is, what was intended in addition to what could be observed through actions) and may even facilitate information uptake in general by providing a "frame" of shared intent awareness against which ongoing status information may be evaluated [112].

4.6.9 Implementation

Several issues have been alluded to in the Participants, Collaborations and Consequences and Justification sections above. To summarize: the need to report, review and, if possible, revise or approve intent from a range of subordinates or co-workers will take time, cognitive effort and knowledge. If these are not available, then the use of this pattern will fail.

On the other hand, there are frequently a variety of degrees of freedom which can be manipulated to reduce the time and effort required for this coordination, and manipulating these will be important in achieving a viable implementation of this pattern. For example:

- The range of available intents can be pre-articulated and labelled and/or reduced and restricted (and, probably, rehearsed) – albeit at the cost of reduced flexibility in agent behavior. This will both reduce communication time and reduce cognitive effort to understand the desired intent at the time of use or execution.
- Intent can be pre-specified (before the context of use), perhaps along with contingencies, to create a binding "contract" between agents which removes the effort required for articulating intent at moments of intense workload, but at the cost of, again, reducing flexibility.
- Specific human or automated agents can be designated as "coordination" or "management" agents and their time and attention freed up, in whole or in part, to monitor, coordinate and review and approve the intents of others.

- Organizational operations can be configured (again, restricting flexibility) in order to minimize the likelihood of conflict and/or to minimize the impact of off-nominal situations – essentially separating "spheres of influence" so that agents are free to operate with minimal coordination requirements within their sphere, etc.

4.6.10 Examples and Known Uses

Miller has written extensively about the need, methods and consequences of making intent explicit – see especially Miller, in press [108]. The earliest example in his work is the comparison between the US Air Force's Pilot's Associate program [113] – which attempted to avoid the need to make intent discussions explicit by making extensive use of intent inferencing or plan recognition AI – and the US Army's Rotorcraft Pilot's Associate [113] The later program made use of a "Crew Coordination and Task Awareness" (CCTA) display which provided human operators a coarse-grained capability to detect what intents the automation had inferred for them and for itself – and to intervene to cancel or override and replace those intents. This innovation seems, in project experiments, to have improved user acceptance and trust in the system – which itself provided performance improvements. The CCTA is illustrated in Figure 4-24 and the comparison between the Pilot's Associate and Rotorcraft Pilot's Associate in their methods of coordinating pilot and system intent is described extensively in Miller (in press) [108].

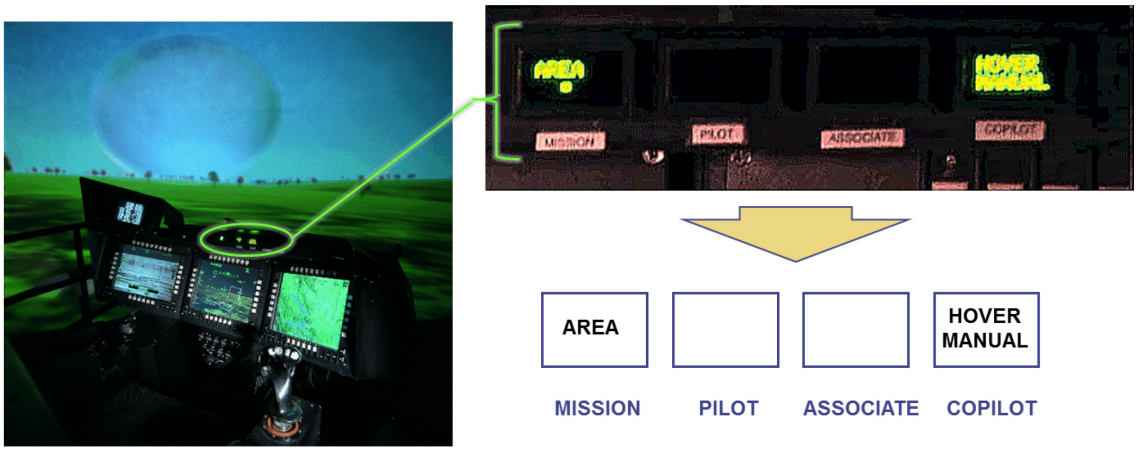

Figure 4-24: The Crew Coordination and Task Awareness (CCTA) Display in a Full Mission Simulator for the Rotorcraft Pilot's Associate Project.

Note: The left-hand image shows the co-pilot/gunner's cockpit with the position of the four alphanumeric buttons which comprised the CCTA circled. On the upper right is an enlargement of the CCTA, while the lower right provides a constructed schematic depiction of the text and labels on the buttons of the CCTA to compensate for poor image quality.

4.6.11 Related Patterns

The Explicit Intent Communication pattern is almost certainly related to, and a more specific type of the more general "Transparency" pattern being articulated by Chen and Barnes in this volume. It is also in contrast to what might be viewed as a hypothesized "Intent Inferencing" pattern in which intent is not explicitly declared and coordinated between agents, but is rather left to be inferred on the basis of observable actions and known plans or mental models.

The Explicit Intent Communication is also related to, and a more specific type of, the Bi-directional Communication pattern being articulated by Shively and Coppin in Section 4.3. Specifically, a claim for this pattern is that a useful type of information content to communicate about bidirectionally is explicit intent. Similarly, the design pattern for Working Agreements in this volume is also related in that working agreements are a convenient and formalized method of articulating and establishing a priori agreements on intent across multiple parties.

4.6.12 Conclusions

The Explicit Intent Communication pattern seems to fit nicely into the proposed template and to offer reasonable, if somewhat abstract, advice to potential HAT designers. The augmentation of Schulte, Donath and Lange's [17] representation schema with solution patterns as suggested by Miller [108] seems to offer significant added value, but some of Miller's other suggestions (e.g., augmentations to the type of worker/tool relationships) seem to offer less value. The addition of a pattern illustration using UML Use Case formalisms. One of Miller's proposed modifications is to provide both a problem pattern and a solution pattern. The problem pattern is a description of the "competing forces" [113].

4.7 POTENTIAL SOLUTION 5: INCREASING URGENCY (EXAMPLE: STEPWISE INTERVENTION / ERROR CORRECTION)

4.7.1 Intent

Provide a means for an assistant/associate system to mitigate erroneous behavior of an operator by a stepwise increasing intervention/support. The interventions of the assistant/associate system ranges from alerts, messages, and suggestions up to overrides in order to transfer a dangerous situation into a normative (safe) one. The stepwise approach serves to keep the operator vigilant with respect to the task, and as long as possible responsible for task accomplishment. Another objective of this stepwise intervention is, to avoid a degradation of the final work result. This is possible as long as the error caused by the human has no direct/immediate negative on the overall work objective. For this reason, we suggest a stepwise error correction only for errors which are still repairable before they result in a degradation of the overall work result. We consider two kinds of erroneous behaviors:

1) Errors which occur when the human omits to take a necessary action (error of omission); and
2) Errors caused by a wrong selected, wrong executed, or not at the right time executed action (error of commission).

The type of intervention depends on the urgency. As each task has a certain time window to be executed, the elapsed time of an omitted or wrong executed task plays a major role in the choice of the adequate intervention of the assistant system.

4.7.2 Motivation

Highly automated systems, which are able to detect human errors, are typically designed in a way that they immediately correct human errors. This approach dispossesses the human operator of his/her task immediately, independent whether the human operator has still enough time and mental resources and the ability to correct the error on his own. If such an error correction occurs more often and reliable, this may cause complacency effects in the human. The human may put an overly high trust in this automation, therefore neglect his own tasks and consequently lose vigilance or situation awareness [115]. These negative effects of an immediate error correction

can be avoided by an active involvement of the human operator into the error correction process. Therefore, this design pattern suggests a directed, stepwise-escalated error correction approach in order to support the human operator according to his/her needs and the acuteness of an emerging or an already occurred error.

This pattern will also provide a means for the human-autonomy team to adapt priorities and actions as urgency for completing tasks increases. This implies the need to adapt again, once urgent tasks are completed, become less urgent, or are considered abandoned or obsolete. Critical to this pattern is a definition of *urgency*. Examples are seen in autonomous assists for aviation and driving. An example might occur if the system determines that a collision risk is high from its sensor data. The system can then determine deadlines for the various forms of intervention from models of the autonomy and models of human performance. Here we make the assumption that the autonomy's deadlines are later than the human's. As the human deadline approaches, urgency is increased and the system managing the tasks can invoke actions intended to reduce the risk that the deadline will be missed. These can include notifications, reprioritization of tasks, changes in methods for completing tasks, and task abandonment in the case of lower priority tasks (in terms or reward or cost).

Important to this pattern is a definition of urgency. Consider a model of each available agent (human or machine) capable of performing tasks for the work process. For each task type, the predicted performance for the agent is a probability density function representing the probability that an instance of a task type will require any particular time by the agent for completion.

For each task instance in the queues for the agents, there is a task type, and a required completion time. Tasks can be decomposed into subtasks and methods such as illustrated in the Figure 4-25, if desired, but is not necessary. One could simply consider all tasks as atomic. Urgency of an atomic task is the probability that the task will not be completed on time given the current resource allocation (i.e., what agent is assigned).

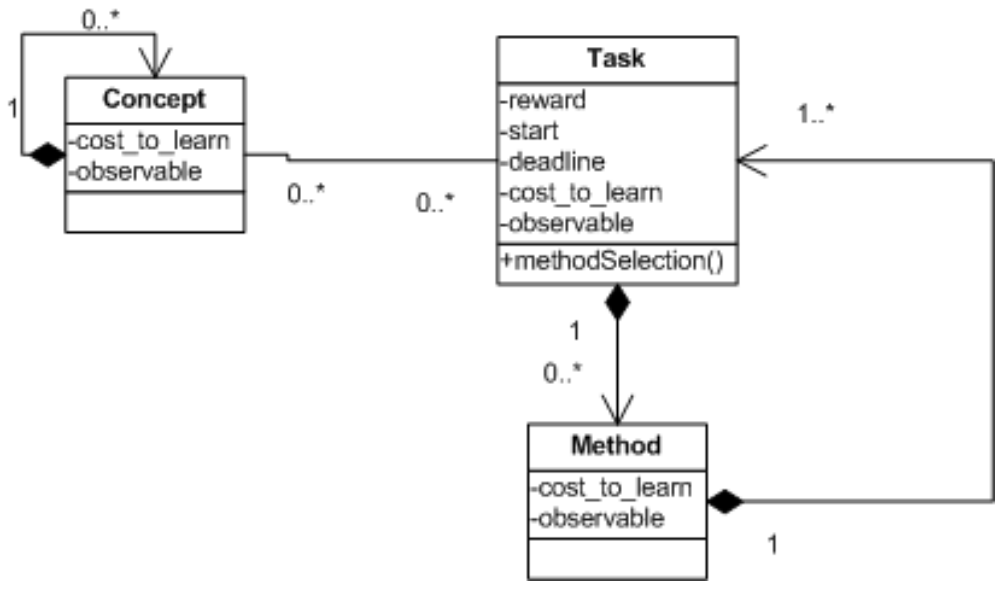

Figure 4-25: Possible Task Structure.

Urgency for a composite task must be propagated based on a task decomposition pattern. Composite Tasks (one model of hierarchical WProc) are composed of methods, with an 'or' relationship. Any one of the methods can

be selected to complete the task. Methods are composed of tasks, all of which must be completed to complete the method. We propagate urgency:

- A method's urgency is the maximum urgency of its tasks.
- A task's urgency is the probability that it will not be completed in time if it is atomic;
- A hierarchical/composite task's urgency is the (median | mean | max | min | E(x) | CoV@R(r, x)) urgency of the methods it is composed of. The exact method is up to the system designer.
- A networked WProc can be modelled using composite tasks for the purposes of urgency. There are at least three subtasks (receive input, perform task, and send output). The perform task is likely to be further decomposed to account for aspects that must wait for input.

4.7.3 Applicability

Use this pattern, when you want to mitigate unwanted out-of-the-loop effects of a human operator, which might be caused if technical systems perform an immediate and automated error correction. Do not use this pattern for time critical support of human operators, where you need immediate function or task adoption by the technical system. This design pattern is more apt for tactical or strategic tasks rather than reactive tasks.

4.7.4 Structure

Figure 4-26 illustrates the collaboration between human and agents or automation within a work system, which enables a "step-by-step" error correction. It uses a graphical language, which is defined in Ref. [17], and in Section 4.2 of this report.

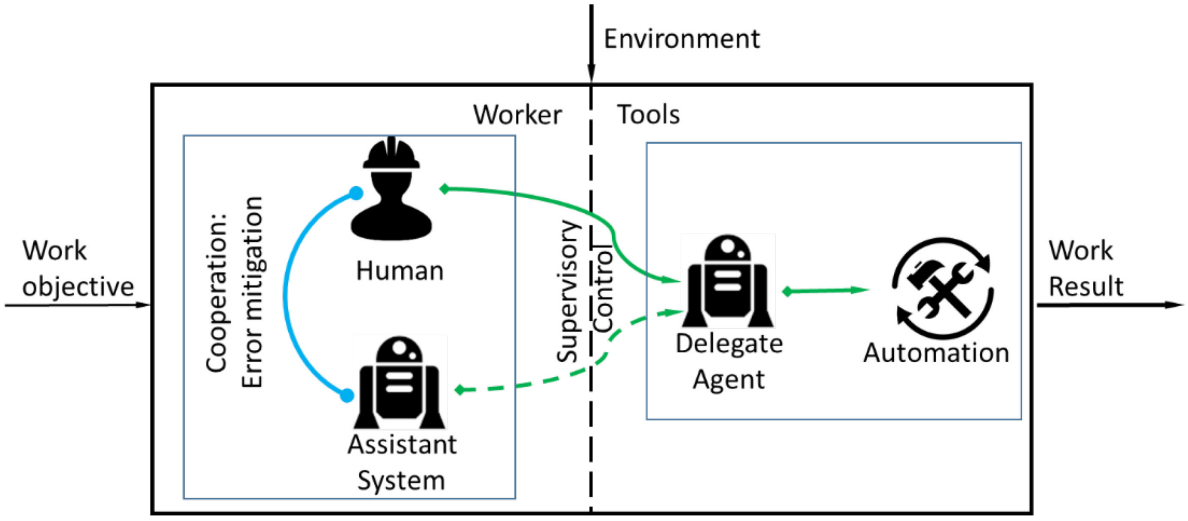

Figure 4-26: The Basic Elements for the Design Pattern "Increasing Urgency / Step-By-Step Error Correction".

On the left-hand side, both the human and the assistant system are workers. Workers know the given work objective. They are able to understand and pursue the work objective according to their abilities. The relation between both workers (human and assistant system) is a heterarchical one (blue connection). Within this cooperation there is no hierarchical gap between the involved workers, each worker acts on its own initiative to

pursue the overall mission goal. In this case, the assistant system continuously monitors the human and the work process, and supports the human step-by-step in the achievement of the overall mission goal. While pursuing the work objective both workers use the available tools. These tools are subordinate to the worker and represented on the right-hand side of the work process. These tools are in a delegation/supervisory control relationship to the worker (green connection). They receive tasks, instructions, or commands which they have to execute in order to achieve the given/delegated tasks. Within this work system we distinct two different kind of agents, which have different purposes [33]:

- Purpose of the delegate agent: Control of conventional automation to reduce human taskload; and
- Purpose of the assistant system: Mitigation, i.e., prevention or correction of erroneous behavior of the human.

4.7.5 Participants

As depicted in Figure 4-26 the participants are a human and at least one intelligent agent, the agent on the worker side, referred to as assistant system.

The human is in charge of the achievement of the given mission objective. The assistant system let the human accomplish his/her tasks as long as no errors (errors of omission, errors of commission) emerge. In case these errors occur, the assistant system will choose an adequate intervention according to the urgency of the task, which has either to be accomplished or corrected. A working agreement (see Section 4.4) can be agreed and in place with the assistant. This allows the human to establish the parameters of how the assistant will behave as urgency increases.

The delegate agent on the right-hand side is optional. This agent is able to accomplish given tasks by use of available automation. If this agent is not available, the interaction of the human or the assistant system is on the level of commands for the available conventional automation.

4.7.6 Collaborations

The fundamental requirement for this pattern is that there be at least one participant that is aware of the urgency and priority of the tasks. This participant should have an agreement with any humans concerning the rules under which autonomous action may be taken. This agreement can be built into the system or created through a working agreement pattern.

4.7.7 Consequences and Justification

This pattern mainly affects the cooperation between the human and the assistant system. The assistant system in general behaves like a restrained human teammate. Within normal situations, the assistant system is no more than a silent observer. Only in situations which require an action of the assistant system to prevent a degradation of the overall mission performance, the assistant system becomes active with a situation adequate intervention. This restrained behavior of the assistant system will keep the human in charge of task accomplishment, as long he/she is able to do his/her task on their own. In due times, which means in times where it is necessary for the human to take actions (e.g., recognition of an effecting change in situation, necessary execution in tasks) the assistant system makes an appearance, by giving alerts, hints, messages without wresting the human from his task. The human will be kept in the loop and supported as long as the human has enough time, resources and capabilities to solve the situation on his/her own.

A possible downside might be, that a human can adapt to the restrained behavior of the assistant system. This means the human will always wait until no more time is available to do the task on his own, which means that the assistant system has to stand in by a full task adoption of the human.

4.7.8 Implementation

For the realization of an assistant system, which provides a stepwise increasing intervention policy, the assistant system has to have the following capabilities [115]:

- Monitoring of the environment and detection and analysis of danger;
- Monitoring of the human and interpretation of the observed data with respect to the human's cognitive state;
- Planning and scheduling of interventions; and
- Execution of interventions, i.e., of the actual interaction with the human.

The interventions of the assistant system shall be supportive but rather reserved. The overall goal is, to keep the human as long as possible in the loop and responsible for task accomplishment. To enable this requirement the assistant system shall express the following desired behavior:

- The human shall be given as much time as possible to find own solution;
- Interventions shall provide input that helps with the current problem;
- Dangerous situations shall be resolved before damage is inflicted; and
- The input given by an intervention shall not exceed the current problem.

In order to choose the emerging conflict situation, the urgency, and the adequate intervention strategy the assistant system has continuously to:

- Determine if the current situation is dangerous and, if so, at what time damage (a violated threshold of certain performance parameters) will be inflicted. A situation is dangerous if the further development, without intervention by the human or the assistant system will lead to a damage (e.g., degradation of the overall work result).
- Determine what the human should do, to resolve the dangerous situation. The resolution typically consists of giving a certain command (sequence) either to an existing delegate agent or to conventional automation.
- Estimate the current cognitive state of the human. The cognitive state includes mental resources such as situation awareness, vigilance, workload and focus of attention. It also includes the state of information processing, i.e., the current task and the associated cognitive processes. These estimates should be based on a model of the human's information processing.
- Compute the transitions of the human's cognitive states leading from the current situation to the resolution of the dangerous situation, and identify the conditions for each transition: What steps will the human's mind have to go through to effect the desired action, beginning with its current state? These steps and estimates of their duration (with buffers and worst-case assumptions) should be based on a model of the human's information processing.
- Arrange these computed mental steps along a timeline, beginning with the earliest one. Arrange them in a way that the final step (the desired action) takes place immediately before the moment of damage,

i.e., barely in time. The position of the left end, i.e., the starting point of the sequence, will then determine the point in time at which the pilot has to begin working on the problem.

- Determine whether the starting point of the sequence is in the future, or not:
  - (Yes): There is still time left for the human to find own solutions. Do nothing.
  - (No): The human should have reacted by now. Intervene by enforcing the current transition, i.e., the first step, using any available means.

Figure 4-27 shows an example of how the assistant system derives necessary interventions. Within this example, a human operator has to enter new commands to his own aircraft to avoid a collision with a foreign aircraft; so the task for the operator is to enter the right evasion commands (2) to avoid the collision. This has to happen immediately before time (1), which is the last chance to avoid the damage. In fact, the human operator is actually analysing his tactical map (3). By monitoring the human, the assistant system could detect that the human did not yet detect the foreign aircraft. The assistant system determines that the sequence of detection, information processing and action, leading from the actual task of the operator to the desired action steps (4, 5), will likely not be completed in time (6a). Therefore, the assistant system intervenes (6b): it enforces the transition from the human operator's current mental state to the next state (detection of a relevant change in the tactical environment) by alerting the human operator about an incoming other aircraft.

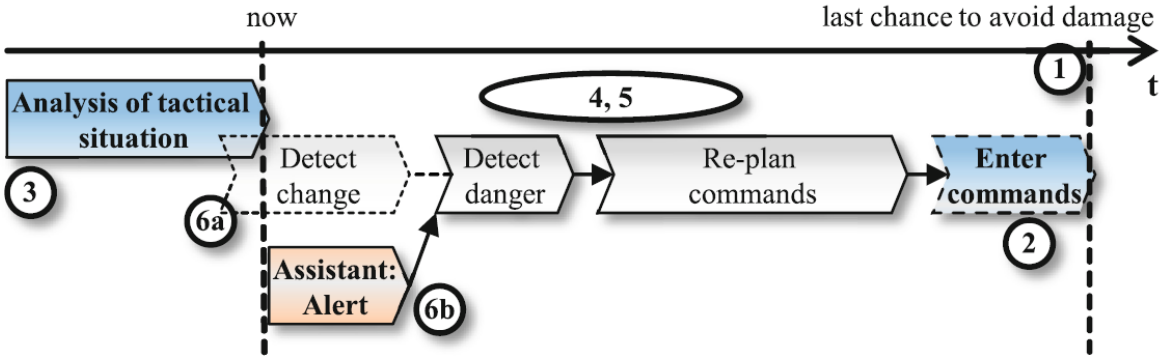

Figure 4-27: Example for Planning and Scheduling of Interventions by the Assistant System.

For each possible dangerous situation, the assistant system has to have a repertoire of different intervention possibilities, for example:

- Neutral alerts without hints to the emerging error situation;
- Directed alert towards the emerging problem;
- Messages and suggestions to give hints to the human how to solve the situation;
- Proposals to adopt part-tasks to support the human in task accomplishment; and
- Complete task adaptations in temporal critical situations.

One possible consideration is that behavior may be different when urgency is increasing and when it is decreasing. The working agreement with the task manager should specify what these behaviors should be [116]. Table 4-6 contains examples of behaviors that may explain this better than a formal definition.

Table 4-6: Examples of System Behavior.

Urgency Range	When Urgency Increasing Since Last Time Step	When Urgency Decreasing Since Last Time Step
0 – 24	No change from standard working agreement.	Treat as having indicated priority. Remove requests to abandon or messages and failure and replace with explanation dialog. If activity on method has not been initiated by human and another method requiring more human action is available that will keep task within this urgency range, then change methods.
25 – 49	If human activity has not been initiated on this method and another method is available that reduces urgency, then select new method.	Remove highlights in lists. Remove requests to abandon or messages and failure and replace with explanation dialog.
50 – 74	Use alert highlighting in lists. Treat as having 50% higher priority in sorts.	If a request to abandon task or a failure message has been presented, remove message. Provide dialog explaining reason for removal.
75 – 99	If there are no task dependent, then request approval to abandon task.	If a failure message presented, remove message and provide dialog explaining removal.
100	Failure message to human. Request extension on deadline or abandonment of task.	Not possible.

4.7.9 Examples and Known Uses

This pattern has been applied to the domain of unmanned air reconnaissance conducted by a single human pilot in a ground control station.

The work objective of the single human pilot was to gain reconnaissance information on certain objects (buildings, persons, vehicles) in a hostile area. The required information could be obtained by using the sensors attached to an unmanned aircraft. These sensors provided video and imaging data to the human pilot. Beside the task of gathering and evaluating sensor data to gain the required information, the pilot has furthermore to manage the flight of the unmanned aircraft. The reconnaissance targets were given to the pilot beforehand, but could have changed during the mission. The execution was furthermore constrained by airspace regulations (boundaries and corridors), threats (possible unexpected hostile air defences), and resource limitations (fuel). As it was a single pilot ground control station, the pilot had to carry out the tasks of flight management, sensor management an interpretation of sensor data in parallel. Therefore, the pilot was supported by an assistant system according to the described design pattern.

Within this use case, the assistant system had to prevent, among others, the following effects of erroneous behavior of the human pilot:

- Violation of airspace regulations by the unmanned aircraft;
- Loss unmanned aircraft by exhaustion of fuel reserves during flight;

- Loss of unmanned aircraft by entry into the threat radius of hostile air defence sites; and
- Ineffective reconnaissance (inadequate fulfillment of the mission objective).

To avoid these effects, the assistant system was able to intervene. It was integrated into the control station's systems and had direct access to the pilot's GUI. Depending on the information processing step of the human determined by the assistant system, the assistant system was able to display general alerts and iconic or textual messages, highlight certain screen elements, direct the pilot's attention to other screens or override commands if necessary. The assistant system gathers all necessary information to plan, schedule and execute an intervention from the subsystems.

For a detailed description of the implementation of the required functionality, please refer to Ref. [33].

Figure 4-28 provides an example of an escalating sequence of interventions of the assistant system, grouping the interventions into five escalating steps, which can occur one after another:

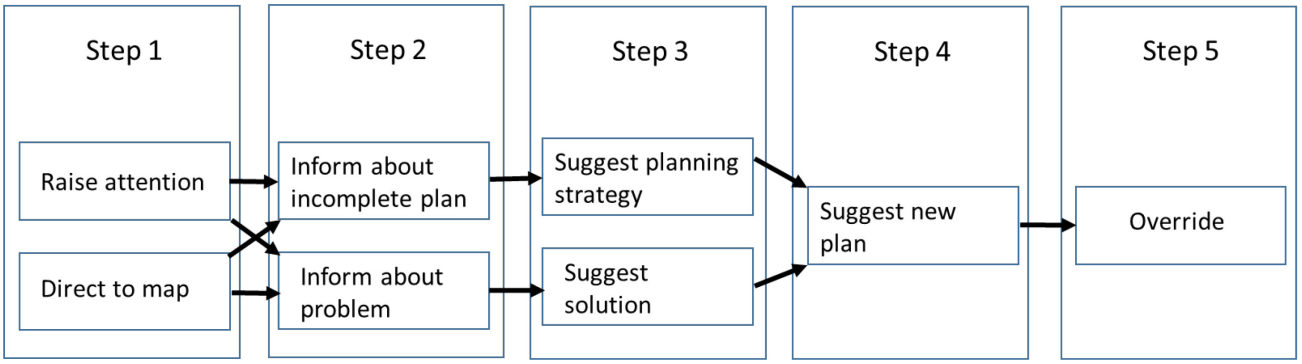

Figure 4-28: Exemplary Escalating Intervention Sequence of the Assistant System [17].

The pictures in Figure 4-29 illustrate one realization of the cooperation between the human operator and the assistant system by applying the stepwise escalating intervention sequence.

4.7.10 Related Patterns

This pattern can make use of *working agreements* to establish the rules by which urgency will be addressed. The formalization takes features from a pattern that might be titled *tasks with deadlines and rewards*. In that pattern, rewards are only received in full if the task is completed prior to its deadline.

This pattern has a complex interaction with the pattern *human takes control upon autonomy failure*. That pattern requires that a method requiring human attention be selected for a task that formerly was being performed by the autonomy. This can cause an immediate increase in urgency. This may be how the user is notified of the need to take control (e.g., a new method is selected when the autonomy fails, this method requires urgent attention, so the task manager tries to reduce urgency by going to the autonomy). To avoid infinite loops, the methods allowing action by autonomy need to be marked as unavailable through some means.

Step 1: Direct To Map: **Visualization of an Arrow Symbol Directing to the Relevant Display.**

Step 1: Raise Attention: **Flashing of Warning Symbol.**

Step 2: Inform About Problem: **Highlighting the Reason for the Danger and Hint in Text Form.**

Step 3: Suggest Solution: **Highlighting Threatened Tasks and Proposal for a Solution in Text Form.**

Step 4: Suggest New Plan: **Plan Proposal Direct Within the Menue. Highlighting of the "Commit"-Button and Hint via Text Message.**

Step 5: Override: **Overwrite of Task Orders, Highlighting of New Task Orders and Hint Via Text Message.**

Step 2: Inform About Incomplete Plan: **Hint with Respect to Necessity of a Re-/New Planning via Text Message.**

Step 3: Suggest A Planning Strategy: **Plan Proposal via Text Message.**

Figure 4-29: Pictures Illustrating One Realization of the Cooperation Between the Human Operator and the Assistant System by Applying the Stepwise Escalating Intervention Sequence.

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Chapter 5 – HAT TECHNOLOGY DEVELOPMENT ACTIVITIES AND LESSONS LEARNED

Gilles Coppin
IMT Atlantique / Lab-STICC
FRANCE

Axel Schulte and Diana Donath
Universität der Bundeswehr München
GERMANY

Marcel Baltzer and Frank Flemisch
Fraunhofer Institute for Communication, Information Processing and Ergonomics FKIE
GERMANY

Mark A. Neerincx and Leo van Breda
TNO Perceptual and Cognitive Systems
THE NETHERLANDS

Rogier Woltjer
Swedish Defence Research Agency FOI
SWEDEN

Robert Taylor, Helen Keirl, Aaron Thorpe, and Antony Grabham
Dstl
UNITED KINGDOM

R. Jay Shively and Joel Lachter
NASA Ames Research Center
UNITED STATES

Summer L. Brandt
San Jose State University / NASA-Ames Research Center
UNITED STATES

Thomas Z. Strybel
California State University
UNITED STATES

Mark Draper
US Air Force Research Laboratory
UNITED STATES

Jessie Y.C. Chen and Michael J. Barnes
US Army Research Laboratory
UNITED STATES

Douglas S. Lange
Naval Information Warfare Center, Pacific
UNITED STATES

5.1 FR-1: TAPAS PROJECT AND COWORK2 METHODOLOGY

5.1.1 Main Context of TAPAS Study and Demonstrator

The context of the **Techniques d'Analyse du Partage d'Autorité des Systèmes de Systèmes (TAPAS) / Analysis Techniques for Shared Authority in the Systems of Systems (TAPAS)** study and demonstrator is the anticipation of the switching of configurations of multiple fighters towards hybrid configurations composed of fighters *and* a fully autonomous Unmanned Combat Air Vehicle (UCAV). The focus of TAPAS has been put on communications, arguing that dialogue problems and shifts in common ground that could be tuned between two human fighter pilots would be more difficult to deal with when introducing autonomous entities in the team.

In this perspective, the envisaged Work Process is seen in Figure 5-1.

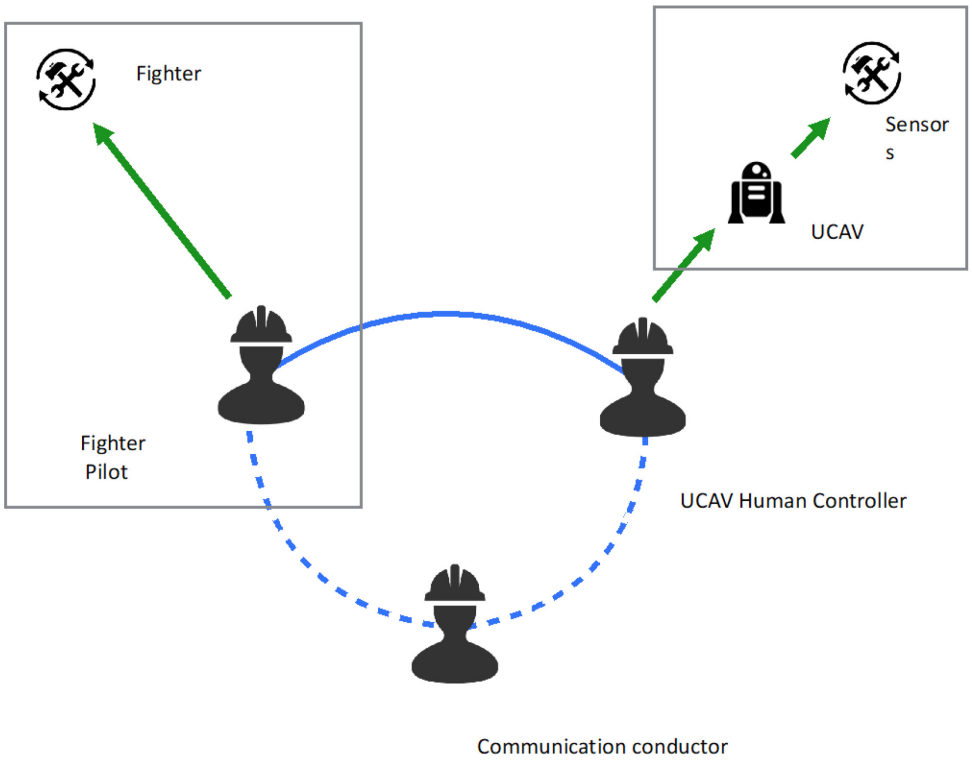


Figure 5-1: Envisaged Work Process.

While the fighter pilot keeps on managing his/her part of the mission, the team is extended with a UCAV operator, in charge of UCAV parts of the mission as well as the communication and synchronization with the pilot. In a future version of highly autonomous UCAV, this second operator could be ignored, and the partial mission and related communication could be directly handled by the UCAV itself. In both cases, TAPAS project makes the hypothesis of a third entity, a communication coordinator (a.k.a. conductor), responsible for monitoring the state of the parties and the adequacy of the communications and for intervening when necessary to align the common grounds of human and autonomy in case of a major shift. This third operator could be replaced by a specific intelligent agent in the future, after learning from both physiological and communication patterns.

In the very first configuration of the system, all three actors remain human, and the TAPAS project has focused on a methodology – named COWORK2 – of extracting meaningful indicators from physiological measurements and communication patterns so as to detect abnormal states and to trigger corrective actions.

5.1.2 Detailed Description of TA

The following paragraphs describe the **COWORK2** methodology applied in **TAPAS** and the first results obtained through an experimentation on realistic simulators of a Rafale fighter.

5.1.2.1 General Presentation of the Method

The COWORK2 method consisted in three main steps:

1) A collective task analysis for military tactical flight;

2) Individual (workload data analysis) and team (communications analysis) data gathering to evaluate Team Performance; and
3) Evaluation of collective tasks from the Team Performance prism.

5.1.2.1.1 STAGE 1: Collective Task Analysis

To analyze pilots' collective work, it is necessary to first describe collective flight tasks. Collective Tasks (CTs) into patrol are highly related to radio communications. Consequently, intra-patrol radio communications could be used to carry out the pilot's collective task analysis [1]. This analysis could be processed with the help of a Subject Matter Expert (SME) on the basis of an allo-confrontation method [2]. Confrontation methods are known to yield a good immersion and data close to the deployed activity [3]. These recorded communications, as well as the tactical and operational information about the flight context, are presented to the SME to retrieve a set of communications standards. The expected result is a definition of the tasks composing the collective work.

The acquisition of a corpus of collective tasks – used as a CT coding scheme (first step of the COWORK2 method) – was a prerequisite for, on the one hand, segmenting the pilot's physiological activity before the workload analysis and, on the other hand, the communication analysis.

5.1.2.1.2 STAGE 2: Individual- and Team-Level Assessment (Toward a Low-Intrusiveness Device)

This stage gathers two kinds of assessment. Team-communication-level assessment consists in the analysis of the radio communication exchanged into the patrol during the flight. Individual-workload-level assessment required the development of a suitable device.

Pilot collective tasks could be examined during actual training sessions in a highly realistic simulation environment. These sessions represented a real stake for pilots who tried to obtain a higher rank (section leader test completion). In this specific context, the deployment of the experimental setup, to assess individual workload, necessitated to respect two main requirements:

1) To be adapted to the simulation environment with high quality data acquisition; and
2) To not disrupt usual flying activity (unnoticed device) and preparation of pilots. One objective of the COWORK2 method consisted in the implementation of a low-intrusiveness experimental setup for a continuous recording of the patrol's leader physiological activity [4].

A major advantage of these measures is to be non-invasive in that it does not interfere with information processing (no explicit request for evaluation of a condition, a specific situation or perception, etc.).

Another interest is the possibility to gather data from low intrusive sensors fitting with the flight simulator activity (no discomfort or annoyance for pilot). In addition, online recording offers a close observation (i.e., with a high temporal precision) of changes in the patterns of physiological activity. Thus, these measures can reflect with some accuracy workload variations and consequently Team Performance variations. Indeed, when an individual is engaged in a cognitive activity, indirect indications of its level of effort may be collected from the changes in the status of a number of physiological variables. These measures therefore provide information that is not contained in performance (outcomes) or subjective measures [5], [6], [7].

A great deal of research has used physiological and/or ocular data to study workload in the field of pilot activity. A higher physiological activation (activation of the sympathetic branch of the autonomous nervous system) – i.e., a higher workload – is then observed between baseline measurement (resting period) and flight

activity and during the most difficult flight phases namely take-off or approaches segments with a high informational load (landing, touch and go). This increasing activation is reflected by an increase in heart rate, respiratory rate, skin conductance, pupil diameter and a decrease in heart rate variability [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18].

Collecting this information, in addition to intra-patrol quality communications, appears highly relevant to detect Team Performance reduction during flight.

5.1.2.1.3 STAGE 3: Team Performance Evaluation of Collective Tasks

The last step of COWORK2 method consists in evaluating the Team Performance of collective tasks from the physiological activity and communications analyses. Different statistical and multivariate exploratory techniques were used to achieve this purpose (Hierarchical Ascendant Clustering, K-means, etc.). Team Performance of collective tasks was considered as endangered when an increase of workload and/or a degradation or uncertainty presence into communication was detected. Figure 5-2 presents the three-stage method and the expected outputs.

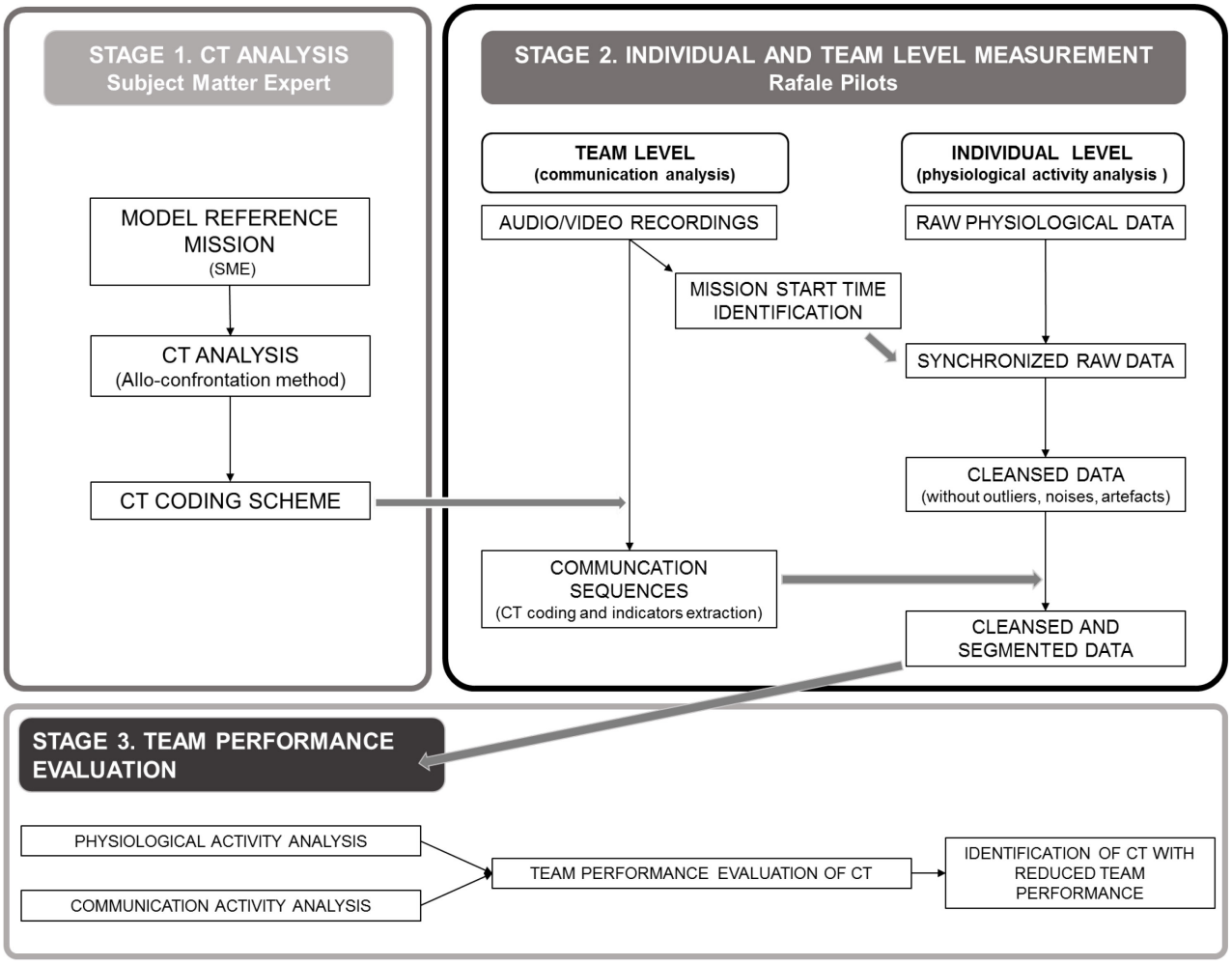


Figure 5-2: Presentation of the Three-Stage COWORK2 Method.

5.1.2.2 Application

Application field of the COWORK2 method within TAPAS project was that of tactical flight simulation during actual training sessions of a Rafale patrol. These training sessions took place during pilot formation. In this evaluation context, flight scenarios were not known in advance because they were adapted according to the evaluation needs. Nevertheless, the training flights were chosen to have a high level of complexity in order to produce a large number of collective tasks (air-to-air or some air-to-ground tactical missions).

5.1.2.2.1 STAGE 1 Application: Collective Tasks Identification

Allo-confrontation was realized by a SME (Lt.-Col., French Air Force attached to Dassault Aviation) from an audio and video recording of a simulated air-to-air training mission made by an experienced pilot (four-ship lead). The collective tasks were then defined in terms of communication sequences; a communication sequence included at least two transmitted sentences.

The studied mission was specifically chosen to cover a maximum of typical CT. SME had a free disposal of all the available information for the pilot during the mission (i.e., visual displays of aircraft outside scene, of cockpit and of pilot actions in the cockpit).

This step resulted in the identification of twenty-nine collective tasks. This corpus is used in the next step as coding scheme to segment communications of each training session. All in all, only twenty-six collective tasks were actually observed after the coding of all communications that were exploited (three collective tasks of the initial corpus do not occur during trainings). The final corpus of collective tasks is given in Table 5-1.

5.1.2.2.2 STAGE 2 Application: Individual Workload and Team Communication Data Acquisition

Population. Five male pilots, all French Navy fighter pilots ranging in ages from 29 to 32 years have participated to the experiments. Participants had an average of 870 hrs. of flying experience whatever the platform (ranged from 700 to 1100 hrs.) and 338 hrs. on Rafale aircraft specifically (ranged from 150 to 500 hrs.).

Table 5-1: Final Corpus of Collective Tasks.

COLLECTIVE TASKS CORPUS
Take-off
Fence-in
Join up
Monitoring
Commit
Engagement
Visual/Blind
Threat
Targeting
Interception
Delouse

COLLECTIVE TASKS CORPUS
Failure
Contact radar faded
Self-protection
Weapon status
Airfield weather and status report
Situation of Awareness acquisition
Radio frequency change
Basic flying
Formation change
Mission management
Handover
In/Out
Check oil
9-line
Landing

Experimentations consisted in twenty-two training missions; five of them were run as pretests. In addition, the data obtained for two pilots had to be rejected due to technical problems (data synchronization difficulty) or poor quality of the signals. Thus, analyses have been performed using data collected from three pilots resulting in nine missions. Experiments were conducted during tactical flight trainings in a highly realistic simulation environment.

Simulator. Experiments were conducted in a Rafale simulator located in the Rafale Simulation Center of Landivisiau Navy Air Base, France. It provides a very high realistic environment with appearance and functions of a real Rafale aircraft (real flight instruments and G-seat). During the training session, radio communications occurred between the leader pilot, his/her wingman (stationed in a similar simulator, in a side room) and controllers (in the instructor's room).

Experimental Setup. Individual workload of the leader pilot was measured from several physiological indicators during each flight training. Cardiac, respiratory, electrodermal and pupil signals were continuously recorded. Cardiac and respiratory activities were measured from a BioHarness3™ electrocardiogram belt worn directly on the skin (adjustable elastic strap). Electrodermal activity was achieved by using two Ag/AgCl electrodes kept at the wrist with a band (Affectiva™). A Double-Tracking Device (DTD) for a more detailed explanation) was used to record pupil diameter information. DTD consisted in coupling two faceLab™ eye trackers (two optical pairs) affixed on a quick-release devoted support. This device would guarantee a maximal tracking coverage over the flight despite of pilot's head movements. Globally, all the sensors (belt, wristband, and DTD) were chosen to comply with experimental field constraints in reducing intrusiveness (discomfort for the participant) and integrated in the simulation environment without impairments of the pilot's activity.

Physiological data were synchronized a posteriori with the training session timeline by means of online audio-visual information recordings. A microphone and two webcams were fixed in the cockpit aiming at that

goal. Intra-patrol communications were recorded and archived at the Rafale Simulation Center (from internal device) and then analyzed a posteriori to identify collective tasks. Figure 5-3 shows the complete experimental setup.

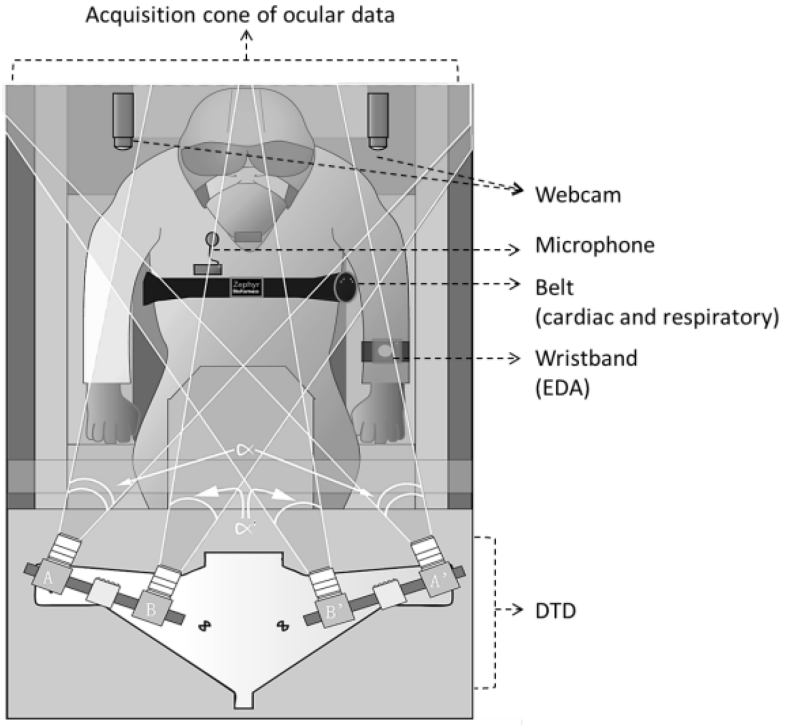


Figure 5-3: Experimental Setup for Individual Workload Assessment.

Note: Audio (microphone) and video (webcams) recordings, cardiac and respiratory measures (belt), electrodermal activity measures (EDA wristband) and measure of pupil diameter (DTD).

Physiological Activity Analysis. All along the simulated training sessions Heart Rate (HR), Respiratory Rate (RR), Skin Conductance (SC) and Pupil Diameter (PD) indicators were recorded. The sampling frequency for each index was respectively 250 Hz, 25 Hz, 32 Hz and 60 Hz.

Communications Analysis. Communications were analyzed through six indicators by counting the number of: spaces in communication (non-procedural silences), hesitations, self-corrections, simultaneous communication to the previous (SCP – pilots interruption), repeat information request ("Say again", one of the pilots queries a response that was not received) and situation report request ("two report", reflect a need to clarify the situation).

All radio communications during flight sessions were transcribed and coded on the basis of the previously defined coding scheme of collective tasks. Physiological and communication data were then divided and processed according to this segmentation. In a second time, physiological data were processed so as to:

- Remove outliers and singular steps out of the domain of physiological validity [4] [19] [20];
- Remove the signal noise: for instance, pupillary diameter signal was cleansed of all light reflexes by using the routine proposed by [21], so as to keep only the cognitive dimension of pupillary response;

- Normalize the interpretable data to erase the differences between subjects (z-normalization for PD, mean-normalization for the other data); and
- Calculate the temporal means (tonic value) for each physiological variable and for each segment of communication sequences. Means were computed considering a time window including five seconds before and after segments to cover residual or anticipation effects on measures.

Lassalle et al. [4] indicated that the whole setup was successfully deployed offering a non-invasive solution to collect high quality data in a realistic flight environment. Nevertheless, study of the signal quality acquisition also revealed a very noisy signal regarding skin conductance probably due to movements' artefacts. As a consequence, SC measures have not been included in the dataset used for analyses.

5.1.2.2.3 STAGE 3 Application: Analysis of Workload and Communications for Team Performance Evaluation

Having processed and normalized physiological data, a Hierarchical Ascendant Clustering (HAC) was used to identify the different classes of collective tasks according to HR and PD patterns variations. Obtained partition was then consolidated by a K-means clustering. Finally, a Friedman analysis of variance (ANOVA) was performed in order to observe between-classes significant differences.

HAC brought five different classes of collective tasks out. Analysis of K-means highlighted the same five classes showing the robustness of the HAC results. Results particularly show the isolation of the "landing" collective task (Class 2) and the grouping of collective tasks corresponding to tactical or combat phases (Class 1) such as the shooting or self-protection ones. CT belonging to class 1 have therefore as common feature to involve the pilot survival or mission achievement. Results indicated that both the HR and the PD were jointly highest in class 1 (Delouse, Threat, Interception, Engagement, 9-line, Monitoring, Self-protection, Targeting, Contact Radar Faded, Situation awareness). However, HR was lowest in class 5 and PD was lowest in class 3 (Airfield weather, Fence-in, Handover and Radio frequency change) and class 2. Class 2, corresponding to the "Landing" CT, is explained by a larger decrease (compared to all other tasks) of the PD. ng.

Table 5-2 give the final centers derived from the K-means clustering.

Table 5-2: Final Centers from K-Means Performed on Physiological Normalized Data.

	Class				
	1	2	3	4	5
HR	,023	,022	,008	,016	,005
PD	,234	-,657	-,383	-,184	,024

Team-Communication-Level Analysis. Team-level assessment consisted in communication analysis from six different indicators. At first, a Principal Component Analysis (PCA) was achieved to detect patterns of contributory factors potentially involved in the reduction of the Team Performance. As previously achieved, it was completed with a HAC aiming at creating different classes of collective tasks. An analysis by K-means and a Kruskall-Wallis ANOVA were then carried out. Figure 5-4 projects the communication-based indicators on the factorial design.

PCA was conducted on the six communication-based indicators: spaces, hesitations, self-corrections, SCP (pilot's interruption), repeat information request and situation report request. Axis 1 explains 36.54% of the inertia. It is determined by the following indicators: "Space", "SCP" and "Self-correction". All these indicators can be considered as errors i.e., gap in communication procedures. Axis 2 describes 20.33% of the inertia. It is determined by "Report situation" and "Repeat information". These two indicators reflect a need of clarification of the situation. Axis 3 explains 15.76% of the inertia and is mainly determined by "Hesitation". Together, these three axes explain more than 72% of the data variability.

HAC was carried out from the PCA three axes. The analysis shows four different classes of collective tasks.

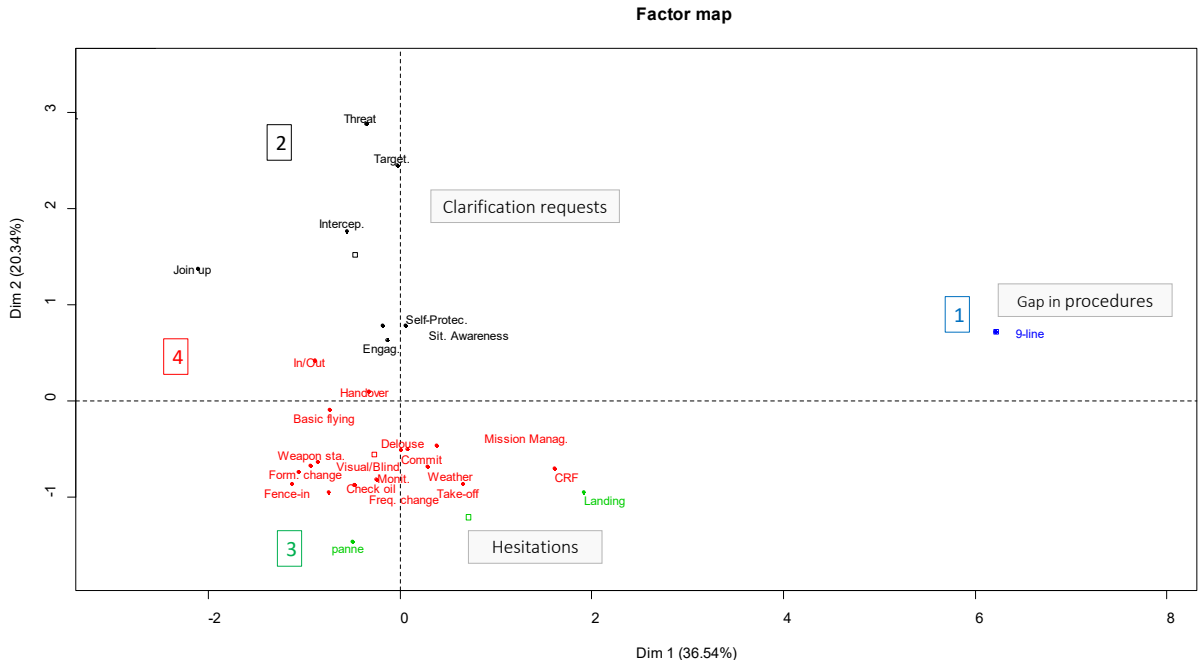


Figure 5-4: Clusters Projected on the Factorial Plan.

Class 1 (Gap in procedures) refers to the 9-line collective task for which an augmentation of these kinds of errors is observed. This task, particularly long, has thus been the cause of a large number of communication errors.

Class 2 (Clarification requests) included collective tasks for which an augmentation of clarification requests is observed. This class includes on the one hand, delicate maneuvers (join up, threat, in/out) and shooting (engage) collective tasks and, on the other hand, tasks for which mission success or pilot survival are potentially threatened (e.g., self-protection). Another interesting point is that, excepted for the "Join up" collective task, all the tasks belonging to this class corresponds to the tasks having entrained both an increase in heart rate and in pupil size (Class 1 of the individual workload level).

Class 3 (Hesitation) is explained by an augmentation of the number of pilot hesitations. Landing collective task in particular belongs to this class.

Class 4 includes the tasks characterized by a significant decrease of "Hesitation", "Report situation" and "Repeat information".

The application of COWORK2 on the experiment field of Landivisiau Navy Air Force provides, on one hand, better knowledge on Team Performance within human fight patrol, and on the other hand, methodological contributions to identify the collective tasks with reduced Team Performance at both individual and team levels.

Team Performance in Fighter Aircraft Patrol. At the individual workload level, results showed that pupil diameter and heart rate tend to increase during the collective tasks related to tactical phases (interception, engagement, self-protection, etc.) compared to more routine tasks of collective work such as airfield weather management, radio frequency change, etc. This implies an increase in mental workload and then a potential decrease of the Team Performance over tactical phases. It seems therefore necessary to support the collective work during these particular tasks for which the Team Performance could be weakened by an increased workload which could be detrimental to the information acquisition and shared situation awareness. The routine tasks could be considered as highly automated and therefore very inexpensive for the pilot. Mouloua et al. [22] report that if the negative effects of a high workload on performance are well documented, low workload could also affect performance because of pilots' vigilance diminution.

Otherwise, the decrease in pupil diameter observed for the landing task tends to indicate a state of fatigue. This last finding is at variance with the literature data that generally report an increase in mental workload (inter alia, reflected by a PD increase) during landing which is one of the most dangerous flight segment [23]. However, literature data are collected during either civil flights or military flights (with predefined scenarios) but not necessarily tactics flights or flights carried in truly immersive conditions. As part of this study, the training flights are tactical military missions (undefined scenarios) performed on a highly realistic simulator and integrating into the pilot training course to reach a higher rank. The challenges of training were therefore important. Thus, the landing which marks the end of the mission (i.e., the end of both the combat critical period performed in a highly realistic simulated environment and the evaluation time) could reflect a state of fatigue for the leader pilot expressed through physiological indicators. Results showed that Team Performance presents a higher risk to be reduced during tactical tasks, based on the finding of an increased individual workload. But the observation of a fatigue state during the landing could also lead to a decrease in the performance of the team during this flight task in particular.

At the team communication level, results firstly showed that the communication procedures were globally followed. Errors (i.e., gap in communication procedures) occur during one collective task in particular. This one is a long and tedious task during which the pilot has to repeat a number of information given by the controller. This step is particularly crucial for a good team situation assessment and a good common ground understanding of the mission and its objectives. Results show that communication quality is degraded during this collective task and could affect Team Performance.

Otherwise, quality of communication decreased during the landing collective task as showed by the augmentation of pilot's hesitations. This can be explained by the release/fatigue occurring during this final phase also noticed on the basis of individual-workload-level assessment. This observation confirms that a reduced Team Performance could occur during landing.

Finally, team-level analysis also showed an increase of the clarification requests (report situation and information repetition requests) during high tactical collective tasks – i.e., for which mission success or survival is directly engage. In other words, this observation confirms the presence of uncertainty into the team and the pilots need to reduce it to perform tactical tasks. It is interesting to note that the collective tasks characterized by an augmentation of clarification requests are also (except one) characterized by an increased workload. These tasks, crucial for the mission well-achievement, can thus be classified as endangering Team Performance both from the point of view of induced individual workload and quality of the team interactions.

Team Performance Assessment Tool: Introducing a Role of Conductor. On the whole, TAPAS results have emphasized tasks of patrol collective work for which the Team Performance was weakened by a workload increase and/or a team interactions quality decrease. As a consequence, COWORK2 method can be used to evaluate, in a posteriori or real-time fashion, Team Performance of collective tasks.

The application of the method especially showed that it could be very relevant to detect the collective tasks with reduced Team Performance that can be caused at individual and team levels. The combination of the two complementary analyses, related to workload and communication, provides a reliable multicriteria means to classify tasks. A prototype of tool, that would be dedicated to the communication coordinator has been proposed in a very first version and is represented on Figure 5-5. A "waterfall" representation, displayed on the left, indicates the successive actions (using a dedicated color code for each kind of actions) as well as related communications sequences. This representation is enriched with a synthetic display of physiological states of the operators (note that in a future case of autonomy teaming only one human operator would be represented), synchronized with the flow of actions and communications, and allowing to an expert "conductor" to detect biases and problems in the teaming.

5.1.3 Summary of Any NATO Communications/Collaborations/Interactions

	Planning/Design	Execution	Analysis
Communication	X	X	X
Coordination			
Collaboration			

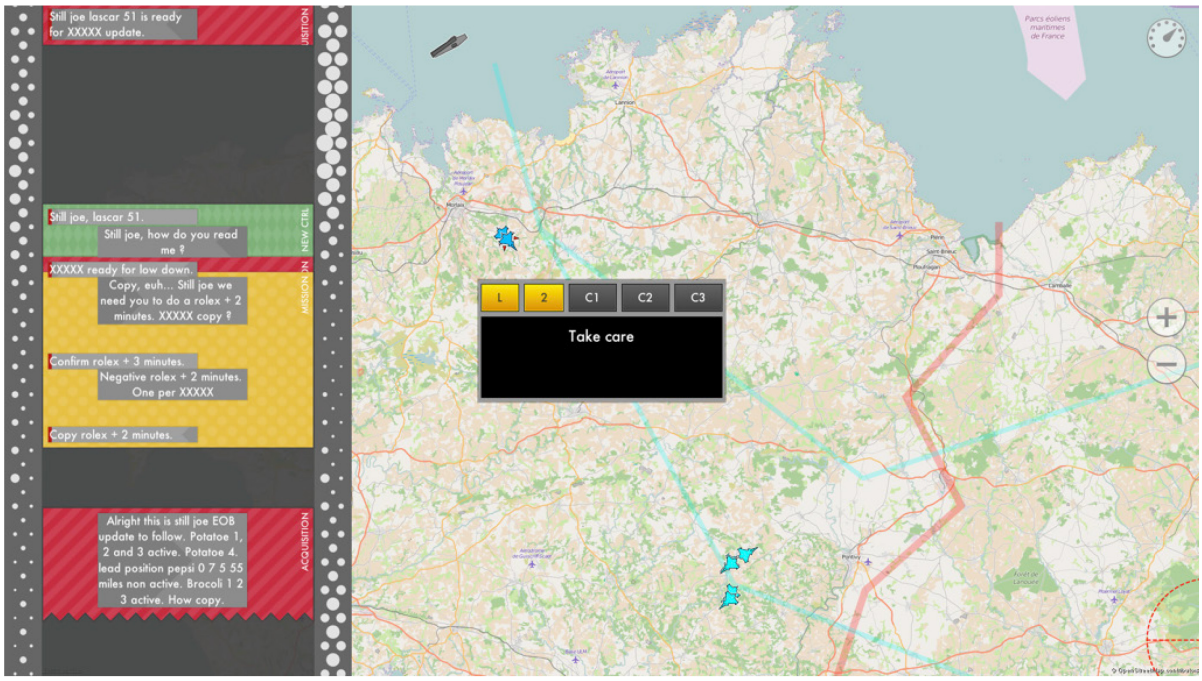


Figure 5-5: Prototype of Communication Conductor Between Two Pilots.

5.1.4 Acknowledgements

The TAPAS project (Technique d'Analyse pour le Partage d'Autorité dans les Systèmes des Systèmes / Analysis Techniques for Shared Authority in the Systems of Systems) was supported by French National Research Agency (ANR) and French Defence Procurement Agency (DGA) and involving Dassault Aviation and the Lab-STICC research laboratory. Project would not have been possible without the approval of the Navy air base at Landivisiau (France) and the assistance of all the members of the Rafale Simulation Center team.

The present report is inspired from the article "COmmunication and WORKload analyses to study COllective WORK of fighter pilots: the COWORK2 method" (Julie Lassalle, Philippe Rauffet, Baptiste Leroy, Clément Guérin, Christine Chauvin, Gilles Coppin and Farida Saïd), published in *Cognition, Technology and Work*, Springer Verlag, 2017.

The prototype of conductor tool has been designed by François Legras from Deev Interaction company as a contribution to the TAPAS project.

5.2 GER-1: SCALABLE AND ADAPTIVE AUTONOMY

5.2.1 HAT Design Pattern Description

Figure 5-6 illustrates the work system for the realization of scalable and adaptive autonomy, applied to a manned-unmanned teaming setup, in which a manned helicopter crew uses multiple unmanned aerial vehicles to fulfil a given mission (e.g., a Combat Recovery Mission).

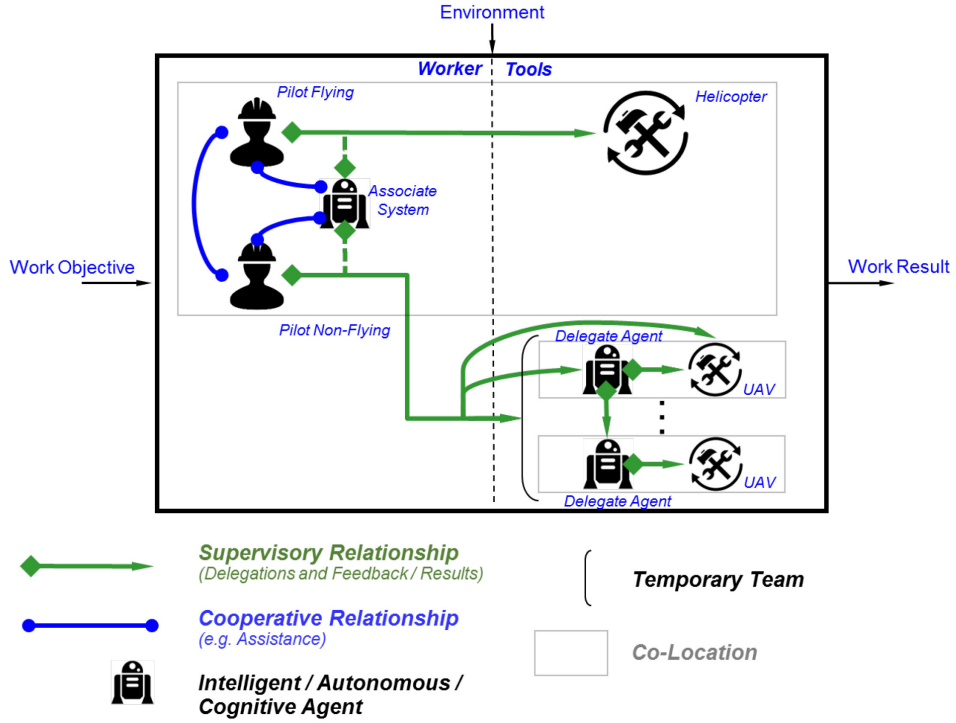


Figure 5-6: Scalable and Adaptive Autonomy Depicted as Work System Representation.

As depicted on the left side of the work system, both pilot flying and pilot non-flying are supported by an associate system. This associate system supports the pilots in their particular tasks and according to their actual needs, during the mission planning as well as during mission execution. The associate system deduces the need and the amount of support based on detected critical mental states of pilot flying and pilot non-flying and adapts its support according to the actual needs (i.e., adaptive autonomy). The support of the associative system can extend on various levels from attention guidance, to simplification of tasks up to entire task adoption.

On the right-hand side of the work system (Figure 5-6) several agents (i.e., delegate agents) are introduced on the tool-side (Unmanned Air Vehicles, UAVs). These delegate agents offer the possibility to the pilot non-flying to guide the UAVs on a task-based level, instead of a waypoint-based level. By guiding UAVs with tasks, the workload of the UAV operator (pilot non-flying) will be reduced and it enables the pilot non-flying to operate multiple UAVs simultaneously for the mission accomplishment. However, task-based guidance requires cognitive capabilities on board the UAVs like planning and problem solving. To realize these cognitive capabilities intelligent cognitive agents are introduced, which are able to understand the delegated tasks, to section the given tasks into adequate subtasks, to execute them and to provide the operator with expected and adequate task feedback (e.g., pre-processed reconnaissance information), similar like a human subordinate would perform such given tasks. As this tasking of UAVs can range from specific low-level commands to a singular UAV, over higher-level tasks to singular UAVs, up to high-level tasks to teams of UAVs, a broad range of automation levels is offered to the operator (i.e., scalable autonomy). By offering this flexibility in the guidance of UAVs, the human operator can tailor his guidance according to his/her preference and to the actual situation.

In case, a new work objective (e.g., mission order) is given to the work system, both pilots (pilot flying / pilot non-flying) start mission planning activities according to their responsibilities. While the pilot flying is responsible for the helicopter, he/she starts planning the helicopter route, as well as necessary radio communications. This planning occurs in cooperation with the associate system, which also knows the given work objective, by using a mixed-initiative approach. Therefore, both, the pilot flying and the associate system, are working actively together (i.e., cooperative relationship) in order to generate a mission plan, which considers all known constraints and limitations (see mixed-initiative mission planning). In parallel, the pilot non-flying starts planning the operation of the UAVs by delegating tasks or commands to the UAVs. In doing so, the pilot non-flying gets support of the associate system in form of proposals (i.e., cooperative relationship). The associate system suggests UAVs, which are best suited for certain tasks, it verifies if the chosen task allocation to the UAVs leads to a violation of timing constraints, or a violation of the overall mission accomplishment, and it gives adequate feedback to the operator as needed. Subsequently, the resulting mission plan and respective tasks are delegated to the automated systems (e.g., helicopter) and the delegate agents (i.e., supervisory relationship).

During mission execution, the associate system continuously checks the processing of the mission plan. It monitors the pilot flying and the pilot non-flying in their actual task performance and therefrom derives an estimated mental workload of both, which is subsequently used to adapt the support of the associate system. Furthermore, it identifies missed tasks and calls the crew members' attention to the required tasks. The associate system additionally supports the pilot flying in re-planning activities in case of situational changes. However, the pilot non-flying is supported in supervising of the UAVs during mission execution. Therefore, the associate system suggests tasks for the UAVs as soon as they are in an idle-mode (i.e., cooperative relationship). An additional support is given by the delegate agent. It offers a guided operator access (see scalable autonomy), to avoid potential upcoming conflicts in tasking of the individual UAVs, which might result in a violation of mission constraints.

5.2.2 Detailed Description of TA

Recently, new operational capabilities were investigated to make military helicopter missions safer, more efficient, and economic. One approach, pursued within this context, is the use of multiple UAVs as remote sensor platforms for reconnaissance and exploration purposes. Guided by the commander of the helicopter cockpit the task spectrum of the commander is extended to a mission manager, UAV operator, and evaluator of sensor images, while some of the original tasks of the commander, like radio communication and navigation, are shifted to the pilot flying. These additional tasks on both sides can lead to at least temporary mental overload conditions and might result in potential performance decrements. To avoid performance decrements, to reduce workload and to support both, pilot and commander, additional automation is necessary. Therefor we suggest a twofold approach by introducing scalable and adaptive autonomy.

Scalable autonomy offers the commander of the helicopter the possibility to guide the UAVs on different abstraction levels, ranging from singular commands, over task-based guidance, up to team-based guidance. For the realization of scalable autonomy, intelligent cognitive software agents are introduced on board the UAVs (right side of the work system, Figure 5-6).

Adaptive autonomy, realized within the associate system (left side of the work system, Figure 5-6), supports the human crew of the manned helicopter. This associate system should act as an additional, artificial crewmember. Therefore, it has to be able to know and pursue the given work objective, to monitor and detect critical workload states of the crew and to supervise and interact with the available automation in order to support the crew in their task accomplishment according to their needs.

5.2.2.1 Scalable Autonomy

Main goal of using scalable autonomy is to provide variable levels of automation tailored to the current needs of the commander of the helicopter (i.e., the pilot non-flying), instead of using a fixed level of automation during the whole mission execution. For the variable level of automation, we examine three different levels: parametric commands, task-based guidance, and team-based guidance.

Parametric Commands refer typically to an individual tasking of singular UAVs, e.g., by presetting of a certain direction for the UAV, a halt/circling command at a certain point, or even a guidance of the UAV on a waypoint level. This low automation level enables the human operator to have a direct control of the system but restricts a cognitive agent on board a UAV by having only a small leeway in decision making. Using this level of automation leads to a higher mental demand for the human operator guiding the UAV. Although a higher level of automation would reduce the mental demands of the human operator, previous experiments have shown that there are occasionally situations during mission execution, which require more flexibility and a direct control/intervention possibility by the human operator [24], [25].

Task-Based Guidance is used to reduce mental demands of the human operator in guiding UAVs [24]. It extends and abstracts the typical waypoint-based guidance, which is commonly used these days. Therefore, it requires cognitive capabilities like planning and problem solving on board the UAVs. With task-based guidance, the commander of the helicopter will command cognitive agents on board the UAVs by committing tasks to the UAVs within a delegation relationship, similar to working with human subordinates (i.e., supervisory control [26]). Therefore, the agents have to understand the given task, decompose this task into subtasks, and execute them in an automatic way, and also return possibly already pre-processed reconnaissance information to the operator.

Team-Based Guidance further increases the span of control in the guidance of UAVs. Within team-based guidance, the human operator gives orders to the team of UAVs. The team of UAVs distributes the implied

subtasks, it coordinates itself temporally, spatially, and according to their available resources, in order to fulfil the given mission task, and it informs the human operator about the task progress and accomplishment.

For the realization of scalable autonomy Rudnick and Schulte [27] suggest a hierarchical approach based on Hierarchical Task Network Planning (HTN Planning). This approach enables the human operator to guide the UAVs on a high abstraction level, while having a direct control and intervention possibility of functions on a lower automation level. Providing this span of scalable autonomy enables the human operator to guide and deploy their UAVs tailored to the actual needs, while maintaining situation awareness about the actual mission progress and UAV task status. Therefore, it increases operator acceptance in the guidance of multiple UAVs.

Within the scalable automation, the operator allocates abstract mission tasks (e.g., reconnaissance tasks) in form of task orders to the cognitive agents on board the UAVs. By giving the tasks to the UAVs, the operator advices the system his/her intents and goals. The agents deconstruct the superordinate task into subtasks and execute the resulting plan automatically. The operator is able to adapt the level of automation during task accomplishment of the UAVs, tailored to the actual task situation. Furthermore, this approach enables the system to pursue the intents of the operator and to detect errors which enables the associate system in the overall work system to suggest a suitable course of actions.

The crucial question in the realization of scalable autonomy is how to design the intervention/acting possibilities of a human in scalable autonomy, while avoiding typical problems, which might occur in the interaction between human and automation. According to Rudnick and Schulte [27] a naive approach, which means allowing an operator to simultaneously intervene on all levels of automation (i.e., on all HTN levels), bears the risk of conflicts between UAV resources and the violation of mission/task constraints, or rules (e.g., the violation of timing constraints within mission tasks, which might result that the origin plan cannot be meet anymore). Therefore, we suggest a situation dependent restriction of the intervention possibilities to the human operator. The human operator is provided a guided access to the hierarchical task tree, represented within the HTN planning. The operator is only allowed to intervene on certain task/automation levels which are suitable to the current situation and which fulfil the mission/task constraints [27]. The implementation of this scalable automation is realized as knowledge-based system based on the Business-Rule-Engine Drools [28]. The handling of the UAVs occurs via a user interface on the tactical map realized as a touch-sensitive multi-functional display.

5.2.2.2 Adaptive Autonomy

The second approach to support a human crew in manned-unmanned teaming missions with multiple UAVs is the use of an adaptive associate system, which is able to adapt its support to the current task situation and the mental state of the crew. By working cooperatively together with the human crew, the associate system is able to detect and correct, or even proactively obviate human errors. In doing so, typical human cognitive capabilities such as planning, perception and understanding of the actual situation as well as reasoning, are now required within the associate system.

5.2.2.2.1 Expected Behavior of an Adaptive Associate System

It is expected that an adaptive, cognitive associate system should behave similar like an ideal human teammate. This means it should understand and pursue the given mission objective by own initiative and thereby considering the workload of the human. Onken and Schulte [29], [30] define basic behavior principles for the behavior of such an associate system. The behavior principles describe an escalating hierarchy, starting with a passive restrained behavior, to the guidance of operator attention, to task simplification and finally to task adaption.

- ***Passive Restrained Behavior*** (0. Basic requirement of associate systems). Each intervention of an associate system means an additional load to the operator including a context switching, which might lead to a decrement in situation awareness and extra work demands. For this reason, such an intervention by an associate system should occur as rarely as possible.
- ***Attention Guidance*** (1. Basic requirement of associate systems). Only if the attention of the operator is not directed to the currently most important task then the associate system should guide the attention of the human towards this task.
- ***Task Simplification*** (2. Basic requirement of associate systems). If the human is temporary overtaxed and therefore not able to execute the current task in a correct manner without any help, then the associate system should simplify this task in such a way, that the operator is again feasible to solve this task.
- ***Task Adaption*** (3. Basic requirement for associate systems). Only in the case of a too high-risk situation, and the costs of a potential task omission would be intolerable, then the associate system should completely adopt the task by own initiative.

To realize these basic requirements within an associate system the system has to have the capability to know both, the current task situation, and the current mental workload state of the operator. This requires a real-time, automatic determination of the mental workload to detect critical workload states, and a detailed representation of tasks to be accomplished by the human, as well as the capability to detect the actual task the human is concerned with.

5.2.2.2.2 Task-Centered Approach

In order to support human operators adaptively, according to their actual needs and according to the above stated behavior rules, an adaptive associate system has to have the capability to derive critical workload states of the operator on the one hand, and the underlying task situation in which this critical workload situation occurs on the other hand. Both information is necessary to offer adequate support to a human operator. Therefore, we suggest describing the workload of human operators not only by a numerical value, but rather in conjunction with the corresponding task situation. Therefore, the tasks constitute a central element within an associate system. The explicit representation of tasks can serve for both, to derive the workload perceived by the operators, and a latter task simplification/adaption by agents to support the human. Tasks draw on the human. They require a certain amount of resources of the human (e.g., mental, auditory, visual, and psychomotor) to execute the task. The amount of required resources and the workload perceived by the human during task execution vary depending on different factors like individual experiences, day's condition, motivation, task complexity, and number of tasks.

Tasks are the driver for human workload, but for a technical system, tasks can also be a central communication interface. The underlying idea is, that a technical system like an associate system needs to have a mental picture of tasks similar like a human has. This mental picture comprises among others, the outcome of accomplishing the given task, the prerequisites required to process the task, the ways the task can be processed, whereby the task can be recognized and the average subjective workload involved with this task accomplishment. Whereas a human has an intuitive idea of tasks and the things involved with it, the technical system has to be provided with all the required a priori knowledge. Basis for this is a holistic task modelling.

5.2.2.2.3 Task Modelling and Context-Rich Operationalization of Mental Workload

Usually, available methods operationalizing human mental workload express the construct by a singular numeric value. However, this is only of little use within a technical system like the described adaptive associate system.

Adaptive associate systems should detect critical workload situations of the human on the one side, but also should take adequate actions to reduce operator workload in these situations. Like human teammates, such an associate system would at least need the actual and maybe the subsequent task context to be able to take adequate actions. For this reason, Schulte [31] specifies an approach to describe human workload not only as a scalar numerical value, but by a context-rich description, including a set of parameters. This enables an associate system to estimate the workload induced by the task the human is currently concerned with and to provide an adequate and situation adapted intervention to support the human in these critical workload conditions.

Therefore, we suggest that context-rich workload description constructed out of the following four components:

1) A description of all tasks necessary to accomplish the mission, given by the mission plan;
2) The task actually performed (called activity) by the human;
3) The required mental resources (e.g., visual, auditory, cognitive and psychomotor) for task accomplishment; and
4) Typical behavior patterns associated with this task accomplishment (i.e., normative task behavior patterns vs. workload-adapted behavior patterns).

The required a priori knowledge for this description is gathered within extensive knowledge acquisition experiments and questioning of military helicopter pilots [32], The work objective (i.e., the mission goal) is decomposed stepwise into required subtasks down to elementary tasks, according to the work of (e.g., Matern [33], Johannsen [34]), and by using the hierarchical task analysis HTA [35]. The highest and most abstract level of the task model is represented by mission tasks like route reconnaissance, which again consists of several pilot tasks and tasks for the automation (e.g., UAVs). The associate system uses only the identified pilot tasks. Pilot tasks distinguish from automation tasks in such a manner, that they additionally consider cognitive tasks like mission planning or the supervision of system states of the helicopter or the deployed UAVs.

Within the task model of the associate system, each pilot task is represented by properties, relations to other tasks, limitations for the execution of the task, evidences for the recognition of the task, required mental resources and associated behavior patterns (Figure 5-7).

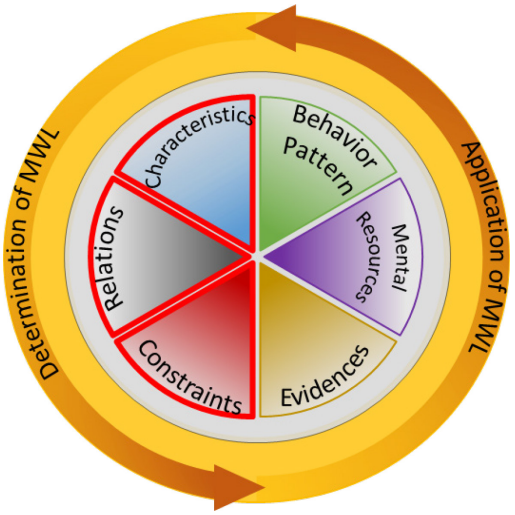


Figure 5-7: Task-Centered Assistance.

5.2.2.2.4 Mission Planning

The goal of the mission planning is to determine the required tasks to move from an initial state to a defined goal state, which then achieves the given mission objective. The mission planner (i.e., the mixed-initiative planner) is a major component of the task-centered associate system [36]. This planner supports the pilots in the planning phases and serves to achieve operational benefits like saving of time and flexibility and reduction of crew workload. This mission planner knows the mission objective (mission goal) to be achieved. It plans on the level of mission tasks represented in the task model and links the required mission tasks causal, spatial and temporal to one mission plan which achieves the given mission goal. The required knowledge about the prerequisites, limitations and relations of tasks extracts the mission planner from the task model.

Typical problems with automated planning are the complexity of the problem space and human factors issues especially if the planning occurs on a high level of automation. A fully automated mission planner can indeed reduce the workload of the pilot, but it can also cause problems like loss of competence [37], [38], deficient transparency on side of the automation [39], lack of understanding [40], or loss of plan awareness [41] In the extreme cases, a highly automated mission planner can lead to an inversion of the hierarchy in plan execution, which means that the human merely follows the instructions of a planner [36].

Therefore, the essential requirements for the realization of a mission planner is to find an efficient solution for the complex planning problem in real-time, and to avoid, or at least minimize human factors problems.

5.2.2.2.5 Approach: Mixed-Initiative Mission Planner

The solution of the complexity problem within the planning is solved by a reduction of the planning problem. In many times, it is not essential to find an optimal plan, but a sufficient good one, which is able to fulfil the given mission goal; according to the Simons Satisficing Principle [42]. The satisficing principle implies the limited rationality of a human who is not able to completely capture complex environmental situations within an appropriate time span [36]. For this reason, humans usually not search for an optimal solution but for a sufficient one, which they can achieve with their available mental resources. Using this approach within an automated planner results in fast planning results although having a complex planning problem. By using this satisficing approach, dynamic re-planning during mission execution can be achieved in real-time.

To address the human factors problems of automated planners, we suggest a mixed-initiative approach. Within mixed-initiative, the human and the automation plan the mission together and both, the human as well as the automation, can take initiative to change or improve the plan. As the planner considers the scalable autonomy, it offers additionally various levels of intervention in order to balance pilot workload during the planning process.

5.2.2.2.6 Implementation of Mixed-Initiative Mission Planner

For the technical realization Schmitt and Schulte [36] use a PDDL-based planner [43] as a primary planning tool. This planner sets the required mission task into a causal relation to solve the planning problem. Afterwards the constraint optimization solver CPLEX [44] optimizes the planning results with respect to their constraints / auxiliary conditions. This can be for example minimizing of threats for the manned helicopter, timing demands for plan alternatives, demands on resources (e.g., UAVs), or the consideration of geo-specific features like terrain or population density. The user interface for the planner uses the same visualization of the tactical map on the multi-touch displays as it is used by the commander of the helicopter for the task-based guidance of the UAVs. Any pilot inputs to the planner will be considered as logical constraints.

5.2.2.2.7 Pilot Monitoring and Activity Recognition

Motivation and Problem Statement of Activity Recognition. The mission plan comprises the necessary tasks the pilot has to accomplish to achieve the given mission. Depending on the actual situation, the actual task of the pilot (activity) may deviate from the anticipated pilot tasks of the mission plan. To detect this discrepancy automatically, and to distinguish between intent and error, it is necessary to automatically determine those tasks/activities, which the pilot is actually executing in real-time. Furthermore, the activity recognition serves as a basis for the determination of the actual required resources.

Approach: Evidence-Based Activity Recognition. As cognitive tasks are not direct observable, an indirect approach of evidence-based task/activity recognition is pursued [45], [46]. During the execution of tasks, the pilots interact on multifaceted ways with the system, e.g., interaction with the flight controls, buttons, screen interactions on the multi-functional displays, radio communication, but also visual attention allocation to the cockpit instruments. During these interactions, the pilots are observed with different measurement sensors. On the basis of these measurements, corresponding evidences, which argue for or against the execution of certain tasks, are collected and afterwards combined. For the acquisition of these interactions we use different measurement sensors, all of which have different reliability. These different reliabilities have to be considered and they have to be weighted differently. For example, manual interactions like button presses can be measured electronically, and therefore are most reliable. However, the measurement of control inputs (stick, collective, pedals) is more complicated, as typically a minimum of movements is sufficient to maintain the attitude of the aircraft (e.g., helicopter). On the other hand, minimum movements of the controls are also induced by feedback of the control surfaces within a flight in bumpy environments. The audio interactions can be measured with microphones integrated in the headsets of the pilots. These measured audio interactions typically show a random noise and interferences, induced by the environment, which leads to measurement uncertainty. Cognitive tasks like the supervision of UAVs or engine instruments in the cockpit constitute another challenge, as these tasks are usually not accompanied by any manual interactions. For this kind of tasks, visual interaction provides important hints. Depending on the eye tracking measurement system, the measured eye movement data can have a great uncertainty. Beside all applied measurement systems, another issue has to be considered. The human behavior itself can be faulty. A simple example for this might be the neglect of necessary entries to the system, e.g., the neglect of entering necessary radio frequencies.

The pilot activity recognition has to deal with all these mentioned uncertainties. Furthermore, the activity recognition has to occur in real-time, which requires high-performance algorithms. This is necessary, that an associate system can cooperate with a human pilot without any disturbing time lag. The real-time conditions in this case are specified by the typical frequency of the conscious mental reasoning processes, i.e., a couple of several hundreds of milliseconds at the most [47].

For the evidence-based reasoning considering the uncertainties we use a simplified form of the evidence theory of Dempster and Shafer [48], [49], [50], [45]. In contrast to probability-based approaches, this theory distinguishes between uncertainty and ignorance and it uses two parameters (doubt and ignorance) to describe information with uncertainty. Based on this theory it is possible to give an associate system the knowledge about his own ignorance. This may offer benefits in such a way, that an associate system is able to explain the pilot if it is not able to give significant recommendations in cases in which it has not enough information.

5.2.2.2.8 Implementation of the Activity Recognition.

The technical realization of the activity recognition takes place on different cognitive levels. At a first step, inhomogeneous measurement data, gathered by the different sensors, are pre-processed by use of signal processing algorithms and then transformed into symbolic observations. This takes place on a sub-symbolic

level. Within this step for each observation, a numerical reliability value is determined by use of a sensor-error model. An example for such a pre-processing might be the pre-processed information: “the left pilot in the cockpit looks on the air-speed-indicator”. “The reliability of this information amount to 90 percent”. Henceforward, the activity recognition takes place on symbolic, logic and knowledge-based level. The logical statements become weighted according to their reliability. Each of these sensor hypotheses serves as an evidence for the execution of a task represented within the task model. The required knowledge for the weighting of evidences is part of the task model. For each task, one or more evidences are deposited within the task model, which specify how strong the evidence argues for or against the execution of this task. By the acquisition of many different evidences it is possible, to logical infer the actual task the human is executing, by applying the rules of combination of Dempster. This rule of combination allows also combining partly conflicting evidences in a meaningful way. A detailed description to the process of activity recognition is described in Refs. [50], [45].

5.2.2.2.9 Determination of the Required Mental Resources

Problem Statement: Determination of Resources. In order to use a resource theory to describe the mental demands within a task-centered associate system, the underlying assumption has to be made, that different tasks require different mental resources and that these resources are utilized with a varying amount.

A manned-unmanned teaming mission is characterized by many parallel tasks to be accomplished by both, the pilot and the commander of the helicopter (multi-tasking situation). One major goal is to determine which mental resources are utilized and their degree of utilization, as well as to identify which resources are still free of utilization or still available. The latter ones, the free or less utilized resources indicate, which or how many additional tasks might be processed in parallel, or to estimate the amount of free capacity of the operator to processes information (i.e., hints, proposals, warnings) to be issued by the associate system. The usage of resources and their amount of usage will be used by the adaptive associate system to decide whether adaptive support is required and how this support and the modality of the interventions shall be designed.

Furthermore, the resource theory offers as one result a singular scalar value for the overall workload. This value can be used to compare it with other data, e.g., psychophysiological data, for further analysis.

Approach Application of Various Resource Theories. Within the helicopter domain, typically multiple tasks in parallel have to be executed by the crew. Each of these tasks will make demands in at least one up to multiple resources. It is most likely that more than one task demands the same resource. To examine the overall resource usage in such a multi-task setting, we apply a resource theory, which is able to cope with multi-task settings. To be able to examine different resources, the resource theory shall distinguish between multiple resources. In principle, these requirements can be fulfilled by applying the resource theory VACP [51]. This theory distinguishes four resources: visual, auditory, cognitive and psychomotor. Multi-task situations can be considered by adding the demands on each resource. A more detailed consideration of multiple resources in dual-task situations is represented in the multiple resource theory of Wickens [52], [53]. This theory furthermore considers potential resource conflicts, which can occur if two tasks mutually conflict with each other. Corresponding conflict values are represented in a conflict matrix. Maiwald [54] extended the original resource theory of Wickens for multiple (i.e., more than two) tasks executed in parallel.

5.2.2.2.10 Implementation of the Determination of Utilized Resources

Using the determined actual task/activity of the pilot, the demand on mental resources can be estimated in the subsequent step. Therefore, the task model is used. It comprises, among other things, the demand vector (eight dimensional), according to Ref. [52], for each task represented within the task model.

So, for the actual (multi-)tasking situation we determine the overall demand within each resource and we determine the resource conflict value [50].

5.2.2.2.11 Behavior Analysis

The behavior of the pilots can also provide useful information with respect to the current workload situation. The behavior is characterized by the way, how pilots execute the tasks. Highly trained pilots show recurring individual behavior patterns in same task executions under moderate workload conditions [42], [55], [56]. However, in high workload situations, the pilots deviate from their normative behavior in the same task situations, which can be used as an indicator for upcoming critical workload/overload conditions [56], [57]. To recognize such patterns, requires an examination of pilot interactions over a certain period. Furthermore, individual pilot behavior models for normative behavior and workload-adapted behavior would be required, which is not yet realized.

5.2.2.2.12 Situation Assessment and Projection of Mental Workload into the Near Future

The goal of the situation assessment is to combine all results from the mission planning, the activity recognition, the determination of resources and the behavior analysis, to project these results into the near future in order to determine a possible adequate intervention.

Therefore, the execution of the mission plan is monitored during mission execution. As the mission plan consists of abstract mission tasks, a detailed action plan is generated by use of the task model. The activity recognition continuously identifies the task of the crew and compares these tasks with the action plan. Therefore, the following results can occur: either the pilot reflects the generated activity plan or not. If so, there is no mandatory need for actions, the activities might be optimized in terms of workload by means of the associate system. If the pilot does not reflect the action plan, we have to distinguish between two cases: The deviation from the action plan is on purpose or unintended due to an error. Wittig [58] shows exemplarily the possibility to automatically recognize the intention of a pilot with certainty-factor model [59].

By using the mission plan as an underlying basis, it is possible to offer assistance not only to the current time, but proactive to the upcoming situation in the near future. Therefore, the required resources for the hypothetic task situations will be calculated and potential resource conflicts anticipated.

5.2.2.2.13 Adaptive Intervention

Problem Statement. The focus of the adaptive intervention is to avoid errors of the helicopter crew and to manage the mission execution productive and safe by using reflected interventions of the associate system. The support of the pilots is geared to the basic requirements for associate systems. Thereby, the associate system has to adapt itself to the mental states of the pilots and to the situation. A detailed description of the adaptive intervention is described in Ref. [60].

Determination of a Need for Action. Prior to the actual intervention, the intervention is planned by the associate system. First of all, it is necessary to determine the need for action. In the process trigger for the intervention are identified. According to Brand and Schulte [60] these are:

- Neglected tasks, which can be identified by comparing the activity recognition with the detailed plan;
- A high demand on mental resources as indicator for workload peaks; and
- An unexpected and immediate change of the situation.

With respect to mission planning Schmitt and Schulte [36] identified three more triggers for interventions:

- If the crew does not start any planning activities, although it is necessary;
- The crew's plans are faulty; or
- The planning of the pilots is suboptimal and deserves improvement.

By using these criteria, critical states can be derived. As a human is only able to a limited extent, to focus his/her attention towards multiple problems simultaneously, the critical system state and the mental states of the operators have to be prioritized according to their urgency. Problems that are more urgent have to be solved with a higher priority. Theißing and Schulte [61], [62], demonstrate an approach in which the urgency of a need for action is geared to the latest possible time for intervention.

Based on this problem identification, it is determined by use of the activity recognition if the pilot is still working on the solution of the problem or not, thus if the attention of the pilot is directed to the current problem. By analyzing the mental resources, it is determined if the crew is able to solve the problem by their own. If so, maybe only if necessary, the attention of the operators has to be guided to the most urgent task, otherwise a support in form of a task simplification or a task adoption is necessary.

Intervention Policies. To guide the attention, different means are available to address different resource channels. To adapt the intervention messages to the still available mental resources of the pilot, we have to determine the actual resource usage of the pilots first. Maiwald [54] presents an approach to conduct messages of the associate system optimal with respect to the pilots' resources, by choosing free or low demanded resources channels and by adapting the modality and the code of associate system messages.

The task simplification and the adaption to the task situation is realized by demonstrating solution strategies, as well as by adapting the level of automation, for example within the mission planning, the UAV guidance and the sensor operation. By means of a higher level of automation the demands of the adapted tasks are reduced and thereby the workload of the pilots. The levels of automation required for a task simplification and a task adoption are provided by the mixed-initiative planner, the cognitive agents on board the UAVs for the UAV guidance and by the sensor and perception management, also located on board the UAVs. On a medium automation level for example, the planner presents suggestions for solutions for valid plans to achieve given the mission goal or suggestions for plans, which achieve the mission goal considerably improved.

Furthermore, the associate system has the ability to fully adopt part tasks or complete tasks within the highest level of automation. Thereby, tasks can be delegated either to the associate system (adaptable), or in case of a too high risk in conjunction with serious consequences, the associate system is allowed to adopt these tasks automatic. Extreme examples are an intervention into the controls to avoid collisions (e.g., with the terrain or obstacles), or the deployment of countermeasures to avert perilous threats.

In the following, an example for the different escalating strategies will be introduced, based on the mission planning. A spontaneous change of the tactical situation usually requires a re-planning of the mission. During this mission re-planning the pilots will be monitored by the associate system. If this mission re-planning is not productive then the planning process will be guided towards the goal state. For task simplification, the associate system suggests a proposal for the adaption of the mission plan, which has to be confirmed by the pilot. An autonomous adaption of a plan proposal will only occur, if otherwise the mission goal cannot be achieved anymore. In case of multiple different and valid plan proposals the mixed-initiative planner gears to the human like decision behavior according to the satisficing principle. This in turn means on the one hand, that the planner does not intervene in case of negligible improvements of the mission plan and on the other hand, that different

situations require different invention strategies. Basically, we assume that the more time-critical the problem is, the less is the requirement for an optimal solution [36].

Implementation of the Adaptive Intervention. The planning of the intervention is realized by use of the cognitive system architecture Soar [63]. This architecture represents as knowledge-based expert system, in which facts and rules are deposited. The rules make sure that the associate system behaves according to the basic requirements for associate systems and the enclosed intervention strategies for the different intervention triggers.

5.2.3 Summary of Any NATO Communications/Collaborations/Interactions

The status of this Tech Activity was communicated to the HFM-247 members during the meetings. We took many initiatives in acquiring common knowledge of system-level framework pattern approach for the entire TG. With US and GER partners there were additional initiatives: cooperation with the US participants in Pattern Approach and with GER participants in Teaming Analysis, and collaboration with US Army Research by exchanging two students for their master thesis.

	Planning/Design	Execution	Analysis
Communication	X	X	X
Coordination	X	X	X
Collaboration	X		

5.2.4 Future Research Needs and Plans in This Area

5.2.4.1 Actual Status and Outlook

The task-based UAV guidance, the sensor management and the task-centered associate system with the key aspects Mixed-Initiative Mission Planning, Pilot Observation, Activity Recognition, Resource Determination and Intervention Generation are implemented prototypical within the helicopter mission simulator of the Institute of Flight Systems at the University of German Armed Forces in Munich. The overall functional chain of the assistance is real-time capable. Within the task model, actual 226 tasks are represented, and 85 asks are possible to be detected by the activity recognition. The system for monitoring the pilots enables to automatically observe approximately 1300 measures. 440 of these observables are actual used for the activity recognition, which again generates 730 evidences. This means 8,6 evidences per task in average. The resource determination also takes place online based on the detected activities/tasks of the pilots. Starting end of this year (2017) extensive simulator trials will take place with helicopter pilots of the German Armed Forces.

5.3 GER-2: COOPERATIVE GUIDANCE AND CONTROL FOR HUMAN-AUTONOMY TEAMING

5.3.1 HAT Design Pattern Description

Cooperation becomes necessary when two or more actors with the ability to autonomous behavior are supposed to work towards a common goal. A successful cooperation is characterized by a consistent, commonly accepted result generated by the actors. If those actors do not work cooperatively, the best result would be two results and the worst none at all. Cooperation is not useful in all situations, e.g., in trivial tasks or tasks with a low resource demand, or in competitive circumstances. Still cooperation makes sense when several aspects of a task require a multiplicity

of abilities or expertise like in interdisciplinary teams that work on complex tasks. Furthermore, cooperation makes sense if the workload for a single actor gets too high and could be reduced by a better balance between several actors.

When talking about cooperative movement, the cooperation or collaboration of at least two actors with the goal of changing the current location is addressed. In Cooperative Guidance and Control a human operator works together with a cooperative automation, which we call co-automation or co-system. Cooperation is enabled by successful interaction. In our concept, interaction is facilitated using an Interaction Mediator [64], see Figure 5-8.

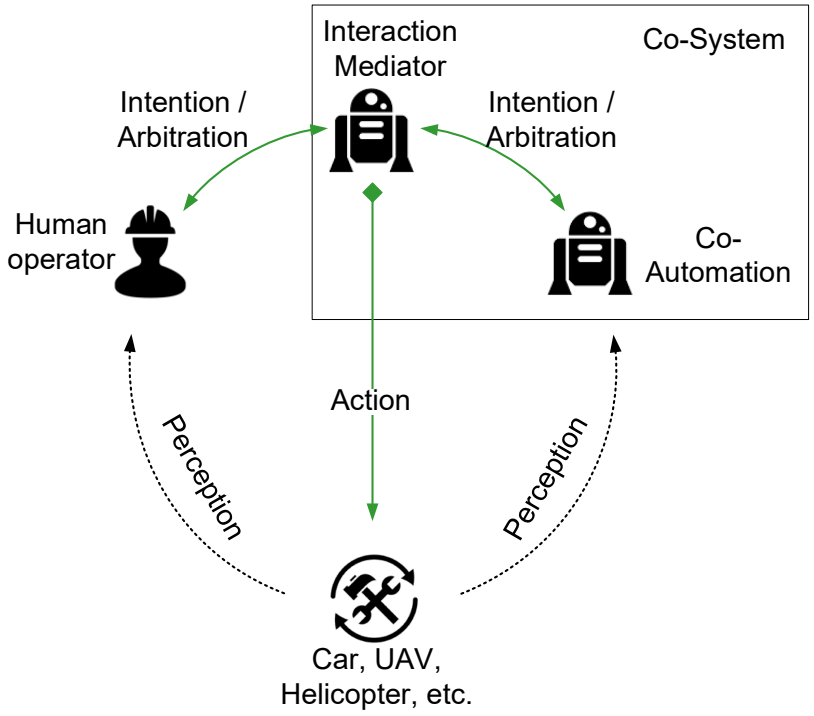


Figure 5-8: Cooperative Guidance and Control (cf. Ref. [65]).

Such a cooperatively guided manipulator like e.g., a highly automated car can either assist the driver, e.g., to maintain an energy efficient state or even take over more advanced driving tasks such as lateral and longitudinal control in varying degrees. In the military domain, these aspects can be extended with system qualities like safety and survivability. When driving for a certain time in a convoy, the workload of many drivers can be reduced to only the workload of the leading vehicle driver, where the others can observe the environment for threats.

5.3.1.1 Cooperative Automation

Ref. [66] already distinguished "Cooperation in action", cooperation in plan and meta-cooperation, which is not directly concerned by current control. Shared control seems to focus on the common task or function on the operational level, e.g., the control level, while cooperation adds the way to take increasingly into account the other agent and the other levels (see Figure 5-9).

More than to know what the other is doing, cooperation allows to have a model of the partner to know how it's possible to cooperate with it/him/her. A cooperative agent (that has know-how to cooperate) can gather

information about the other, analyze this information to decide about their cooperation. Such activity can again go directly back to the operational level, e.g., with shared control. But such cooperative activity can and should be prepared at the tactical and strategic levels.

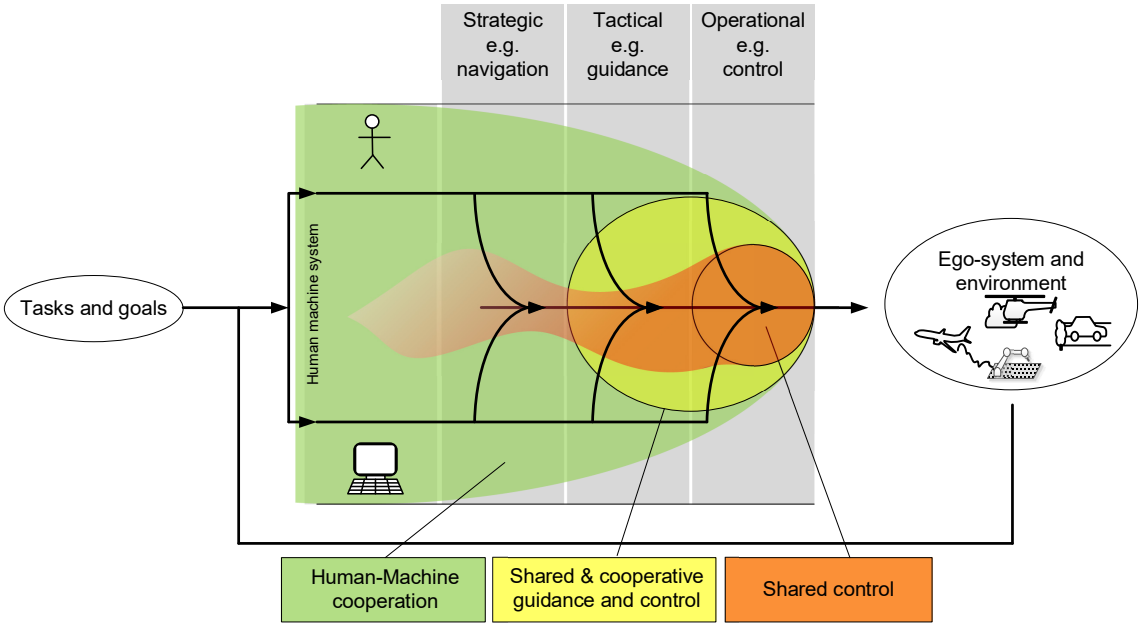


Figure 5-9: Relationship Between the Shared Control, Shared and Cooperative Guidance and Control, Human-Machine Cooperation (cf. Ref. [67]).

An effective way to create cooperation between human and automation is that human and machine have the same internal model of what has happened, what is currently happening and what will happen. This kind of compatible internal models is called cognitive or inner compatibility [68].

Known models to improve inner compatibility were proposed by [69], [70], [71] and [72], that distinguish navigation, guidance and control level of the driving task. [73] combined these to a simplified model of human information processing while guiding a vehicle with the guidance level split into long-term (manoeuvre) and short-term (trajectory) planning in order to enable technical realization (see Figure 5-10).

In this model compatibility results from implementing the structure of human planning and acting into the automation. On the human side perception works over the sensory modalities, whereas the automation needs suitable sensors. Situation assessment is the interpretation of the situation and its projection into the future.

The planning phase can be differentiated into four levels: Navigation, representing the route through the road network; Manoeuvre, semantically determining what next manoeuvre to perform in order to comply to the route; Short-term planning, to generate the trajectory that is according to the manoeuvre; Control, representing the specific commands (steer angle, gas) to conform with the respective trajectory. In order to generate common actions, the intention of human and machine need to be communicated and arbitrated via the interaction resources by the HMI Arbiter on all four levels. How these actions work is determined by the respective automation level. The automation spectrum shows multiple possibilities of task distribution. Examples of mode configurations are seen in Figure 5-11.

As a means to create intuitive interaction between human and co-automation, the interaction mediator uses interaction patterns that will be explained in the following paragraphs.

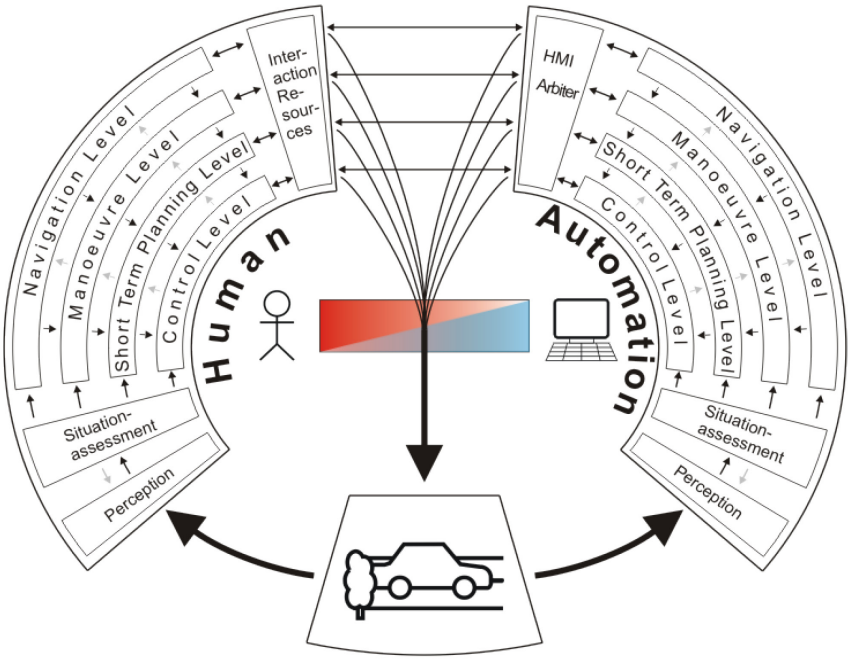


Figure 5-10: Human and Cooperative Automation (cf. Ref. [73]).

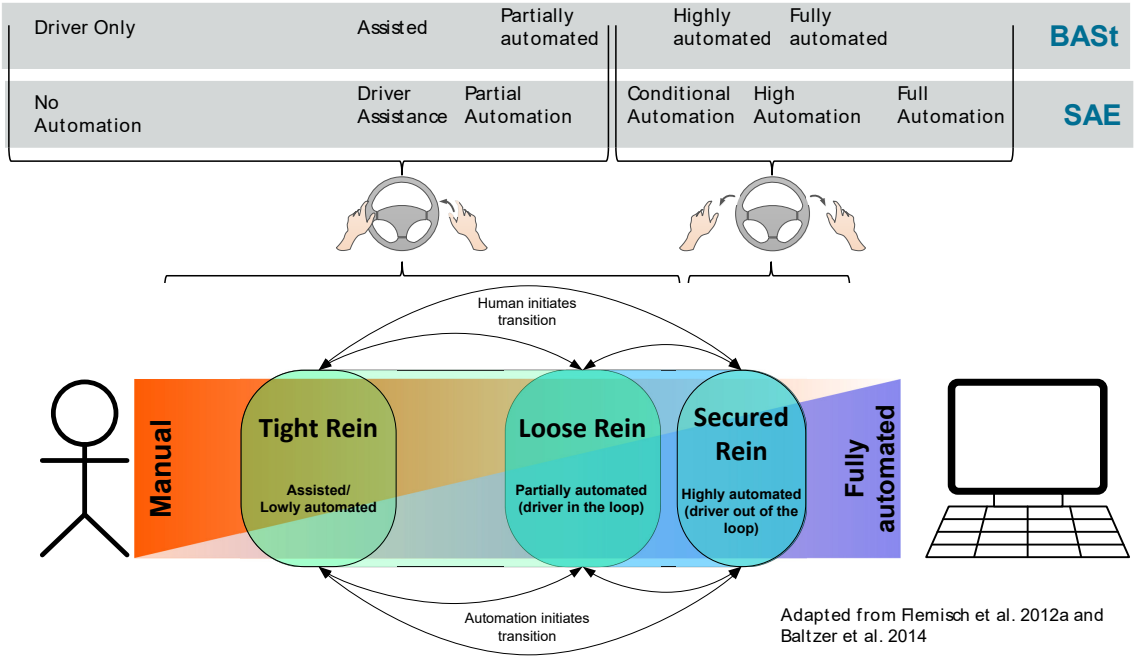


Figure 5-11: Possible Mode Configurations in Cooperative Guidance and Control [64].

5.3.1.2 Interaction Patterns for Cooperative Guidance and Control

Interaction patterns are solutions to given interaction problems described by their use cases. Interaction patterns are described by internal target states in the target domain (see Figure 5-12). These states can e.g., be an understanding of power or urgency. To generate such internal target states in the human, image schemas are used.

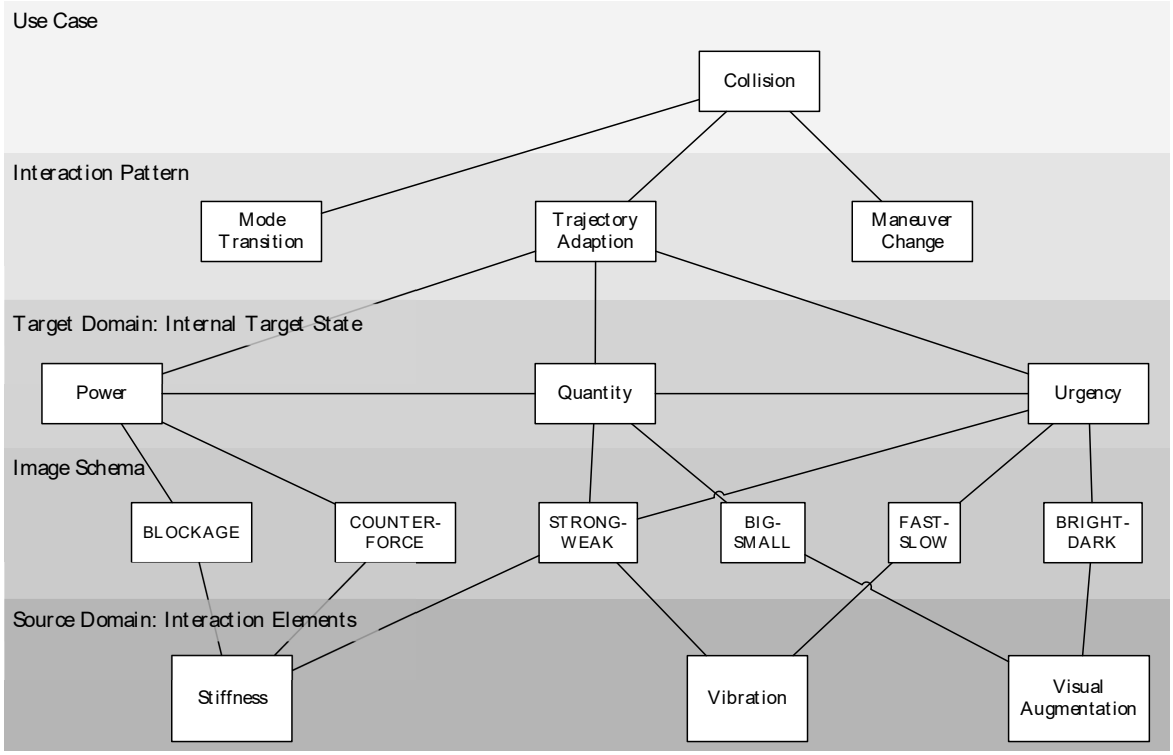


Figure 5-12: A Pattern Language for Cooperative Guidance and Control (cf. Ref. [74]).

Image Schemas originate from our experiences with humans, objects and events in our environment. When visiting restaurants for example we start to generalize things and develop abstract generic expectations about what we can expect from other restaurants. Therefore, when somebody tells us from their restaurant visit, we do not need to know all details like having paid, etc., since we have our own schema of such a restaurant visit filling the missing information with our own experiences.

In another sense Image Schemas are not specific to a certain sensory modality [75], [76]. The so created ambiguity of being abstract (they are schematic) and not abstract (they are embodied) can be solved by understanding image schemas as abstract repeating representations of dynamic patterns of embodied interaction with our environment, that structure our understanding of how the world works. Their strength for human-machine interaction design lies in their metaphorical extension (e.g., importance, power, etc.), so they can transmit more meaning than just affordances [77].

A simple example of an Image Schema is the CONTAINER schema that is built from the structural elements of an INTERIOR, a BOUNDARY and the EXTERIOR [78]. Human understand their body as a CONTAINER with their skin (BOUNDARY) delimiting their inner organs (INTERIOR) from the environment (EXTERIOR)

[77]. This schema can be used for buildings, bottles and a Local Area Network. In terms of design they can be used to transfer meaning between the source domain, e.g., sensory modalities, and the target domain, e.g., speed of action, progress, importance or intensity.

Image Schemas work as a translation between specific bodily experiences from the source domain, i.e., via interaction elements and the abstract target domain, i.e., internal target states. Interaction elements can be described as implementations that generate a certain image schema, e.g., a large stiffness in the gas pedal creates the understanding of a BLOCKAGE, etc.

An Implementation of such an interaction pattern is presented in the following section.

5.3.1.3 Interaction Pattern "Trajectory Adaption"

- Use Case (problem statement):
  - Collision: Object on current trajectory. When state is not changed collision becomes probable.
- Solution:
  - Intervention by automation (autonomous agent) to adapt the current trajectory.
  - Use higher stiffness in the gas pedal to implement the image schemas COUNTERFORCE and in extreme case BLOCKAGE. They are image schemas targeting an understanding of power.
  - The STRONG-WEAK image schema targets the understanding of quantity. Together they build up an understanding of reduced power in the respective direction targeting the internal state that the automation wants to reduce the speed, ergo adapt the trajectory, to prevent a collision.
  - The understanding of increasing urgency is built up by increasingly stronger vibrations in the gas pedal (STRONG-WEAK + FAST SLOW). A visual augmentation uses the BRIGHT-DARK schema with warning color to target once again the understanding of urgency.
- Consequences:
  - Pro:
    - An understanding of reduced power and the shift of control when actively trying to collide.
    - An understanding of increasing urgency.
  - Contra:
    - Shift of awareness from other non-detected threats.
    - High technical requirements (active pedals, contact analogue Head-Up Display (HUD)).
    - Misinterpretation of blockage as a technical defect possible.
- Implementation.

The implementation of the interaction pattern is visualized in Figure 5-13.

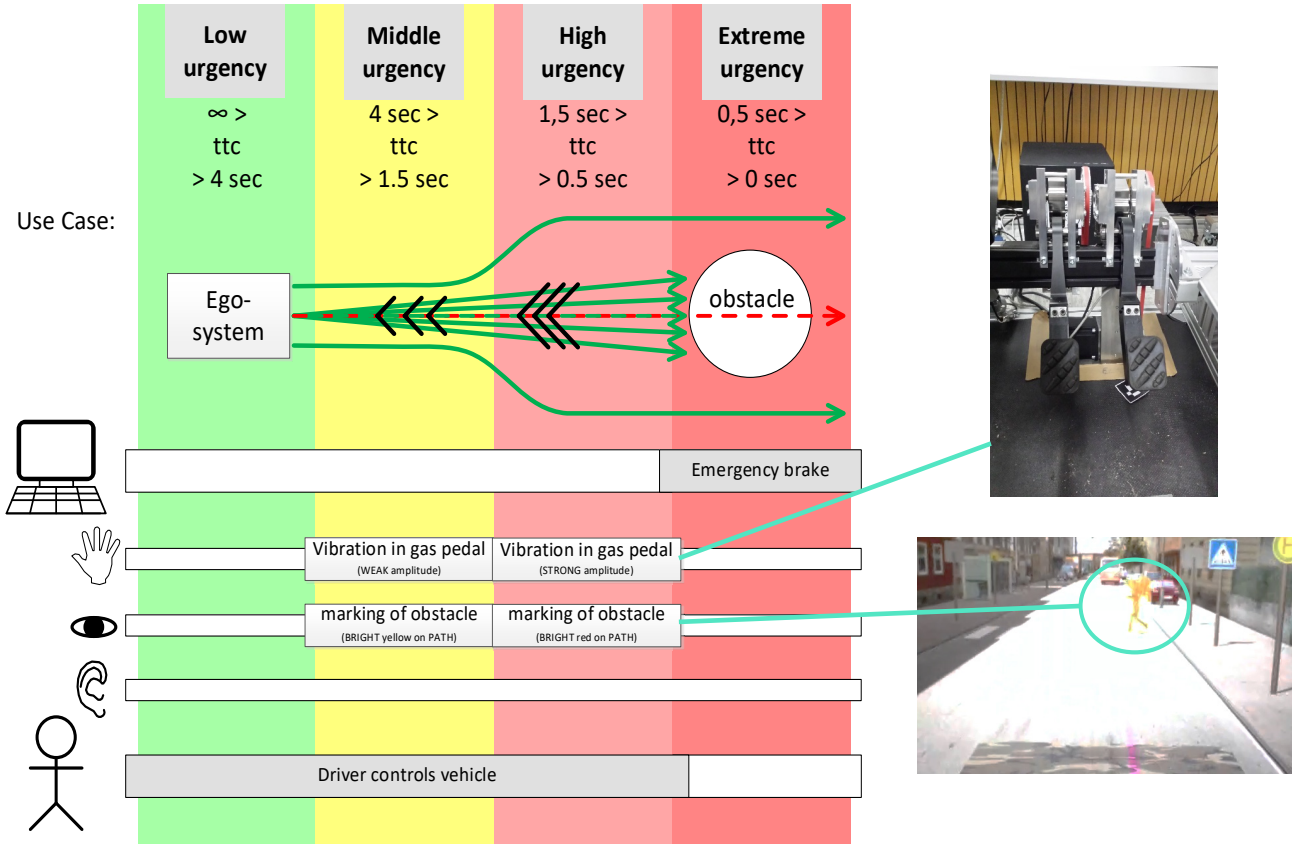


Figure 5-13: Implementation of "Collision Avoidance" Pattern.

In low urgency phases (Time To Collision (TTC), larger than 4 seconds) the driver controls lateral and longitudinal guidance. In middle urgency, a vibration with low amplitude and low frequency in the gas pedal starts. Furthermore, the respective object that the ego vehicle is on collision course with is marked in yellow color on the contact analogue HUD. In high urgency, the amplitude and frequency of the vibration increase, and the marking color becomes red. Finally, in Extreme urgency an Emergency brake is activated, temporarily decoupling the driver.

5.3.2 Summary of Any NATO Communications/Collaborations/Interactions

Status of Tech Activity was regularly communicated to all HFM-247 members during meetings.

	Planning/Design	Execution	Analysis
Communication	X	X	X
Coordination			
Collaboration			

5.3.3 Future Research Needs and Plans in This Area

The next concrete steps to further proof the applicability of the concept of interaction patterns is a further refinement e.g., to find good mappings between interaction elements from the source domain to a certain image schema and the respective internal target state in the target domain.

5.3.4 Acknowledgements

Contents of this work were gained from studies funded by the German Federal Ministry of Defence and the Deutsche Forschungsgesellschaft DFG.

5.4 NL-1: COGNITIVE ENGINEERING METHOD AND FRAMEWORK FOR HUMAN-AGENT PARTNERSHIPS

5.4.1 Capability Description

5.4.1.1 Brief Introduction

Ongoing progress in artificial intelligence, robotics, sensors and network technology feeds the development of, virtual or physical embodied, agents that can act as teammates or so-called *ePartners* during defence, safety and security missions [79], [80], [81]. To operate robustly in hazardous and chaotic environments, these ePartners should show responsible, agile and flexible behaviors in response to foreseen *and* unforeseen events. Furthermore, these behaviors should be fluently integrated into the overall human-agent teamwork, harmonized to the activities and expectations of the human teammates. To establish the envisioned human-ePartner collaboration, ePartners will require an understanding of humans social, cognitive, affective and physical behaviors, and the ability to engage in partnership interactions (such as explanations of task performances, and the establishment of joint goals and work agreements). This section presents:

1) A situated Cognitive Engineering (sCE) method for the incremental development of knowledge base and reasoning mechanisms that establish the desired ePartner abilities and behaviors; and
2) A perceptual-cognitive framework to implement these abilities and behaviors.

The European TRADR project (www.tradr-project.eu) provides an example: The development of an agent-based system for robot-assisted disaster response, in which the response team needs to dynamically adapt the task allocation and coordination to the momentary context [82].

5.4.1.2 Situated Cognitive Engineering

To build on past and current agent systems, and to relate the concerning agent behaviors to each other, it is important to understand agents' design rationales [83]. So-called "design patterns" capture this rationale by explicating common solutions for classes of problems (e.g., as formulated in a use case [84] [85]. In sCE, the pattern specifications include testable claims (where appropriate, referring to stakeholders' values): The effects of agents' behavior on the condition and performance of (the ensemble of) team actors. Patterns can be constructed at different abstraction levels with different types of relationships, forming the building blocks of the research and development of team agents.

First, sCE distinguishes Ontology design Patterns (OPs; [86]) of key domain and human factors concepts. For example, we have been developing human factors OPs for situation awareness [87], task load [88], and work

agreements [89], and domain OPs for task urgency and task complexity [90]. These ontologies underpin the knowledge base ("beliefs") and reasoning of the TRADR agents, for example for proposing, adjusting, accepting, fulfilling or rejecting a work agreement. Second, Team Design Patterns (TPs) specify generic reusable behaviors of actors for supporting effective and resilient teamwork [91]. These patterns can be constructive or destructive, which can be observed in the behavior of an individual or group of actors. During a field test, for example, the TRADR team showed an individual, destructive micro-management pattern of the team leader. By formalizing and implementing this pattern as an OP, the agent can mitigate this behavior in future situations. Third, Interaction Design Patterns (IDs) describe the shaping of the (multimodal) human-agent interactions, such as the dialogue acts for work agreements in TRADR [92] [93]. Fourth, the design rationales with their claims are evaluated via simulation and prototyping, resulting in approval, rejection or refinement of the concerning models. In TRADR, the ontology, team and interaction design patterns have been developed and tested in several cycles, applying simulations and realistic field tests with a complete team, including unmanned ground vehicles and unmanned aerial vehicles. Neerincx [93] provides an overview of some successful patterns, and the remaining challenges for the proposed model-based teamwork support.

5.4.1.3 Perceptual and Cognitive ePartner Framework

As a team member, ePartners need to acquire and show understanding of the meaning, weighting and implementation method of the joint goals they are committed to. This type of understanding and commitment is being built and communicated via three partnership interactions in Human-Agent Teams (see Figure 5-14).

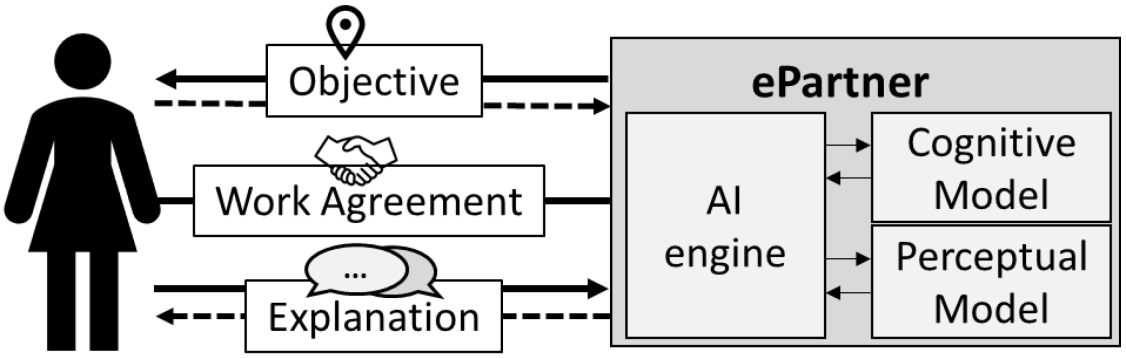


Figure 5-14: Three Human-Agent Partnership Interactions: Objective Sharing, Harmonizing Activities via Work Agreements and Explaining Task Outcomes.

First, active partnerships require the setting, progress monitoring, refinement and adjustment of joint *objectives*, based on a shared understanding, awareness and communication of the objectives and their situated urgencies. Stakeholders' values, strategic intentions and momentary context conditions determine the urgency and feasibility of the objectives to pursue. The choices of the objectives can require re-assessment and adjustment to deal with changing circumstances, possibly just in advance or even during the work processes. Objective ontology design patterns [86] [94] [90] and utility elicitation methods [95] are being developed to support the setting of joint objectives. Adaptivity is an important capability of human-machine teams, which may involve creativity to find a new work process (possibly with an adjusted objective) when the current process is expected to fail. Humans perceive, associate and reason differently than machines; consequently, the perspective-taking and solution space for new (possibly wicked) problems is larger when machines and humans share their perceptions, associations and reasoning.

Second, the proposed human-agent partnerships involve explicit, univocal and possibly adjustable, work agreements on how the tasks should be allocated and performed [89]. In one of the first studies, we developed work agreements for human-robot partnerships in disaster response teams (i.e., in the TRADR project). Such a team needs to dynamically adapt the task allocation and coordination to the momentary context. Similar to the modelling of the objectives, an ontology design pattern has been developed for work agreements, defining the knowledge required for a team member to set, reason about and adjust work agreements. A disaster response field test showed that the fire-brigade officers could specify work agreements as required, which, subsequently, brought forward the desired adaptive team behavior of the concerning robot.

Third, we developed explanation models for ePartners that should invoke adequate trust calibration (i.e., to mitigate over- or under-reliance) and improve the learning of the team members. Currently, a generic Perceptual-Cognitive Explanation (PeCoX) framework is being developed for this purpose [93]. The perceptual level provides an Intuitive Confidence Measure [96] and identifies the "foil" that can be used in a contrastive explanation [97]. Such an explanation fits with human explanation dialogues, centering on the question "Why this output (the fact) instead of that output (the foil)?" It reduces the factors in the explanation to the ones that are of interest to the human, so that it can be better interpreted by the human. The cognitive level provides the beliefs, goals and emotions for explanations [93]. Initial evaluations showed that humans can understand the explanations that PeCoX will provide, but further personalization and contextualization is needed.

5.4.2 Summary of Any NATO Communications/Collaborations/Interactions

Research in team situation awareness, agent transparency and trust calibration has been discussed and aligned with research at ARL, USA (Jessie Chen), among other things resulting into the organization of a workshop on Transparency at the international conference (RO-MAN2017) and a special issue of the IEEE Transaction of Human-Machine Systems on Agent and System Transparency. The requirements, opportunities and constraints of AI Technology that can underpin ePartner's team abilities and behaviors have been explored with SPAWAR, USA (Doug Lange), e.g., during a visit of Doug Lange to TNO, the Netherlands. The general engineering and design pattern approach for HAT has been extensively discussed with UniBW, Germany (Axel Schulte, Diana Donath), e.g., during a visit of TNO to UniBW in München, Germany. Further insight in the requirements of a general human-centered, cognitive work analysis and system engineering, approach for HAT has been acquired in meetings with FOI, Sweden (Rogier Woltjer), particularly on the empirical grounding of the claims on agents' contribution to the team performance.

	Planning/Design	**Execution**	**Analysis**
Communication	*USA, Germany*		*Sweden*
Coordination			*USA*
Collaboration	*USA*		

5.4.3 Future Research Needs and Plans in This Area

Mutual interest in the design, development, and incorporation of patterns such as situation awareness, working agreements, transparency, etc., provides the opportunity to continue collaboration with the people and organizations mentioned in the section above, which is invaluable.

5.5 SWE-1: COMMAND AND CONTROL OF SYSTEMS OF SYSTEMS WITH AUTONOMOUS CAPABILITIES (LASSA)

5.5.1 Introduction

The aspects of Command and Control (C2) and cooperation between human operators and autonomous systems have not been studied to the same extent as technological applications and their potential. In the light of this, FOI performed an exploratory interview study with personnel from the Swedish Armed Forces regarding some of the possible automated or "autonomous"[1] functions and capabilities. These functions were described using "capability cards". Some of these capabilities are already (partially) available, while for others, various technical or operational challenges remain to be overcome. The interview study comprised expected military benefit of and risks associated with autonomous functions and capabilities, related challenges regarding C2, as well as important considerations for flexible and agile[2] C2 of autonomous systems. When possible, the interviewees identified challenges to be overcome in the areas of C2 methodology, steering and control, and C2 systems, to be able to obtain the envisaged military benefits.

5.5.2 Method

The study consisted of 12 interviews with 16 participants in total. The participants were military officers (working in different positions) from different branches of the Swedish Armed Forces, who were interviewed either individually or as a group. Each interview lasted between one and two hours. The purpose of the study was to identify general areas and specific suggestions for further research and development.

The basis for the interviews was a number of *system and capability cards*, developed for the interviews based on different technological forecasts and trend analyses. The purpose of using the capability cards was to provide examples for discussion of possible application areas for automated/autonomous *functions and capabilities* in a Swedish military context in the time frame of 2020 – 2035. The interviewees were invited to discuss automation and autonomy related to functions or capabilities in generic systems groups, rather than at the level of specific technical systems, and could chose and combine the functions and capabilities cards in any way they desired, as well as add other functions to the discussion.

The systems and capability cards covered the following seven generic systems/function groups:

- *Communication systems*: frequency allocation, threat-transmission analysis, allocation of bandwidth, choice of position for transmission.
- *Platforms*: route following, route planning, and defensive measures.
- *Defensive systems*: activation, choice of mechanism, camouflage.
- *IT systems*: updating, back-up.
- *Sensor control*: direction, data collection.
- *Weapons systems*: direct, indirect, target selection, selection of measure/type of ammunition/payload.
- *Logistic systems*: orders, prioritization, maintenance.

[1] The word "autonomous" literally means "self-governing" [98], [99], [100], [101]. As the systems discussed here need some kind of human supervision, "autonomous systems" here refers to systems with a relatively high degree of automated functionality which allows them to perform in dynamic and complex contexts.

[2] For a comprehensive overview of C2 agility, please refer to Ref. [102].

5.5.3 Results

The interview results were grouped in a number of themes, which are presented in this section. In connection to each theme, the research team's suggestions for further inquiry or research to be considered by the Swedish Armed Forces are provided.

Key findings are divided into eleven themes: four themes of general issues regarding C2 of autonomous systems, and seven themes roughly corresponding to the generic systems/function groups:

- Increased complexity;
- Interaction between operator and autonomous function;
- Situational adaptation in relation to varying degrees of automation;
- Sensors and data analysis;
- Defensive systems;
- Kinetic systems;
- Platforms;
- Navigation;
- Communication;
- IT systems; and
- Other issues.

5.5.3.1 Increased Complexity

A heavily increased automation and "autonomy" of different functions risks to increase the complexity in the joint human-technology-organization-system. This entails increased difficulties in command and control as the command of complex systems requires an understanding of the (mutual) functional needs and possible interactions between several coordinating units. Linked to the risks of lessened observability and management the complexity therefore is a risk factor for the command of autonomous systems and a challenge for the configuration of command and control systems. Identified future research suggestions regarding autonomous systems in joint human-technology-organization-systems are:

> *Suggestion 1:* Consider the risks of complexity from a holistic point of view, in procurement, requirements, systems development and systems maintenance in highly automated systems.
>
> *Suggestion 2:* Consider the need for education and training to gain an understanding of the logic in autonomous systems and their limitations.

5.5.3.2 Interaction Between Operator and Autonomous Functions

A number of challenges and risks were identified to designing the efficient interaction between operator and "autonomous" system so that they can function as a team. The interviewees addressed, among other things, the importance of system understanding and the need to be able to manually override the systems. They also addressed the questions of in which way automatic behaviors can be controlled with the current command doctrine, trust in the system, clarity in role configuration and how to achieve predictability in the actions taken

by own autonomous systems for efficient coordination in a changing combat environment. Identified research suggestions for the operators' interaction with autonomous systems are:

Suggestion 3: Investigate how autonomous capabilities can be used for sensor systems through scenario-based gaming.

Suggestion 4: Investigate how autonomous systems are to give the operator an understanding for which factors affect systems' behavior and result in the situational awareness that is needed to take manual actions.

Suggestion 5: Investigate how effective control and trust can be created for autonomous systems without the need for the operator to be extensively trained as a specialist operator.

Suggestion 6: Investigate how future development of autonomous systems can be integrated into C2 systems without having to change the C2 system structure.

Suggestion 7: Investigate common doctrine for joint human-machine systems to operate in a coordinated fashion.

Suggestion 8: Continue to follow the development in the area Human-Autonomy Teaming.

Suggestion 9: Investigate how the C2 of swarms of autonomous units should be designed.

5.5.3.3 Situational Adaptation in Relation to Varying Degrees of Automation

Several participants described the need for flexibility during missions as a central issue resulting from the inherent dynamics and unpredictability of combat. C2 staff must over time depending on the situation be able to adapt/adjust:

1) Unmanned units' and automated functions' behavior;
2) Which units/functions are controlled by which role; and
3) Which functions are automated.

It would be beneficial for autonomous functions to enable this flexibility and disadvantageous if the configuration of the system limits this flexibility. The actions of the autonomous functions should also be able to effectively adapt during unforeseen and heavily degraded circumstances. An identified suggestion regarding the flexibility of autonomous systems is:

Suggestion 10: Study how the introduction of autonomous units affects the flexibility of organizational functions and capabilities.

5.5.3.4 Sensors and Data Analysis

The ability to manually control, adjust and align sensors will likely be necessary also in the foreseeable future. On the other hand, there are benefits when it comes to autonomy in data fusion, sensor optimization, technical coordination of sensors, and data/information distribution to multiple stakeholders. A mix of manual and automated functionality is therefore likely, also in degraded or otherwise challenging conditions. The identified suggestions regarding autonomous sensor systems are:

Suggestion 11: Investigate what needs a platform that is acting in a poorly mapped environment has regarding the collection and analysis of information about its operational environment and how this could be done. For example, such actions could be: identification and prioritization of possible routes or landing zones.

Suggestion 12: Investigate how sensor systems can simultaneously accommodate the information requirements from several stakeholders and command levels.

5.5.3.5 Defensive Systems

Autonomous defensive systems can be instrumental in handling threats in a short time frame. The defensive system also needs to be configured and adapted depending on the situation. Activation and deactivation of transmitting sensors and systems on the other hand is part of the risk assessment that is based on the dynamics of combat and is therefore difficult to automate. Identified suggestions regarding autonomous defensive systems are:

Suggestion 13: Investigate what type of events with "very short time frames" would benefit from autonomous defensive systems.

Suggestion 14: Study how operators can configure autonomous defensive systems depending on situation dynamics.

Suggestion 15: Investigate possible risks associated with autonomous systems using sensor and systems that emit detectable transmissions.

5.5.3.6 Weapon Systems

Some autonomous weapon systems are already available, for example anti-air-systems and missile systems with an integrated offensive and defensive system. Some homing missiles can be seen as autonomous or semi-autonomous. The automation of decisions regarding the use of lethal force is controversial and the legal aspects are still not fully clear. The operational environment, threat level, time dynamics, Rules of Engagement, distance and time to target, predictability, and defensive requirements of the situation are all factors that likely will affect to what degree the automation of weapon systems will be acceptable. It is important to be able to adapt the automation level according to these factors. A challenge also lies in designing automated systems with a balance between efficiency and durational capability. Chains for decision making and implementation of decisions need to be constructed in a way that human operators have a reasonable chance to make informed decisions. Only functions with very short time frames that are critical for the survival of the own unit could be fully automated. The planning process also needs to be adapted to this as decisions regarding changes in the degree of automation most likely will be linked to the Rules of Engagement. Methods and doctrines need to go hand in hand in order to enable handling and use of automated capabilities. Identified suggestions regarding autonomous weapon systems are:

Suggestion 16: Closely follow the development of automated measures and countermeasures.

Suggestion 17: Investigate what kind of decisions for action are meaningful to distinguish and which factors may affect the possibility to automate such decisions.

Suggestion 18: Review each part of the sensor-shooter chain considering the possibility that the concept of dedicated sensors may not be the norm in future systems, which may impact both C2 systems and staff processes and functions.

Suggestion 19: Investigate methods for quicker identification and neutralization of antagonistic UAVs.

5.5.3.7 Platforms

Autonomous platforms entail several new tasking possibilities as well as possibilities to execute traditional tasks in a new and more efficient manner, which the interviewees discussed in a number of examples. The primary use of unmanned systems is considered to be the minimization of exposure and risks to own personnel. The identified research suggestion regarding expected benefits of autonomous systems is:

Suggestion 20: Follow the development of autonomous platforms to see how they may improve the capabilities of the Armed Forces.

5.5.3.8 Navigation

Autonomous following of routes can be conducted in several different ways, many already available. Fully autonomous following of routes only works within very limited and well-defined areas. Other options are that waypoints and alternative waypoints are fed into the system manually, that the system suggests waypoints, or that autonomous systems navigate following manned systems with a certain necessary degree of flexibility. Navigate routes is a balance between effect, risks, predictability and flexibility. Identified research suggestions regarding autonomous navigation are:

Suggestion 21: Investigate the design of route planning support that balances effect, risks, predictability and flexibility.

Suggestion 22: Investigate under what circumstances autonomous following of routes can be accepted.

Suggestion 23: Investigate suitable command levels for autonomous systems for different situations and capabilities, including how the command level can be changed in a flexible way.

5.5.3.9 Communication Systems

Automatic frequency management relieves operators but can also limit their freedom of action in the event of the unforeseen. Furthermore, there is a concern that autonomous communications systems are more complex and therefore also require more extensive planning before use. This means that a balance must be found between simplicity in system operation, freedom of action and the extent of preparation and planning. Identified suggestions regarding autonomous communications systems are:

Suggestion 24: Investigate to what extent a more automated management of frequencies can relieve the operators.

Suggestion 25: Investigate how autonomous capabilities can be utilized to support the configuration and deployment of communications systems and networks.

5.5.3.10 IT Systems

The distribution of data can and should be made as automatic as possible as long as it does not go beyond the boundaries of systems' accessibility and usability. An increased use of sensors for diagnostics and maintenance planning for platforms and vehicles has enabled extended support for planning and prioritizing of maintenance activities, but it also requires an adaptation of planning and command functions. Identified suggestions for IT systems are:

Suggestion 26: Investigate principles for how autonomous distribution of data (in such quantities that it affects the functionality of the system) should be established and how the associated C2 and coordination should be executed.

Suggestion 27: Investigate principles for C2 of automated maintenance systems.

5.5.3.11 Other Issues

The use of AI and self-learning/self-optimizing systems is considered as usable in the planning process and, in the long run, might also be used to increase the degree of automation in general in this regard. Human factors considerations need to be taken into account, regarding for example observability, predictability, and directability, and aiding and amplifying human decision-making processes and capabilities:

Suggestion 28: Monitor the development in self-learning systems in order to decide whether such can be used to support the planning process and possibly to increase the degree of automation in operational systems.

Suggestion 29: Consider the need for better understanding of the human decision-making cycle in dynamic situations when developing and procuring systems that include autonomous capabilities.

5.5.4 Conclusions

The results of the interview study show that the Swedish Armed Forces personnel are well aware of the capabilities and benefits that can be gained by autonomous systems. Several examples were discussed where the expected benefits consist of, for example, new tasking possibilities, increased efficiency, less exposure to risks for personnel, and increased possibilities for actions in high-risk areas. The areas discussed in relation to C2 of autonomous systems were, amongst others, navigation, tasking and collection of sensor data, force protection, weapons systems, communications and IT systems. Many of the automated functions that were discussed related to sensors, navigation, communications and IT systems are already operational or likely to be operational in the near future, while the automation of weapons systems for increased effect is seen as the most problematic function, also from a C2 perspective.

A technical autonomous capability is however not enough to achieve the expected benefits. In order to make autonomous systems work in coordination with manned systems the operator needs to understand, for example, which factors affect system behavior, especially in the case of coordination within a team of manned and unmanned units that needs to follow common doctrines. Several of the interviewees also mentioned and exemplified the potential increase in battle complexity and tempo when combinations of competent autonomous systems would be used. This could lead to an increase in the level of difficulty in terms of controlling the executed actions, as control of complex systems demands an understanding of an increasing amount of mutual functional interdependencies and possible interactions between coordinating units. Furthermore, the inherent dynamics of combat and the potential unpredictability of the autonomous systems behavior as part of a complex system constitute crucial challenges. According to the majority of interviewees, the control of autonomous systems requires among other things the possibility to flexibly define:

1) Which functions and capabilities should be autonomous;
2) Which roles should control these capabilities; and
3) Which functions should adapt or be adapted to form capabilities when confronted with unpredicted or degraded circumstances.

The capability cards that were used during the interviews generally worked well as a starting point for a general discussion about higher degrees of automation within defence systems. Furthermore, future studies are recommended to address the purpose, benefits and risks with automation and “autonomy” of *functions* or *capabilities* (as was done in this study) in order to avoid a purely technologically driven development dialogue. In future studies, there are also possible benefits with identifying further challenges related to problems specific for command and control systems. This can be achieved by employing more concrete scenarios and technical solutions in order to enable mapping of possible variations in the operational environments and corresponding ability and technology solutions that answer to the expected degree of military benefits. Future studies therefore need to combine participants with different backgrounds, for example by having diverse Armed Forces roles participate in different study phases. This will enable an appropriate match between criteria and actual needs for future autonomous systems.

The interaction between various C2 levels, flexible roles and flexible "autonomous" functions is deemed to be of significant importance (echoing, e.g., Refs. [98], [99], [100]), alongside with the formulation of a common doctrine and C2 systems for the use of autonomous systems. Systems understanding is to be considered as important for enabling effective and efficient use of these systems. How to design for observability, predictability, and directability (as also highlighted by Ref. [100]) needs to be investigated further. The use of autonomous systems will affect all stages of future systems development and procurement. Today's systems development approaches are not explicitly designed to consider the potential interactions that can emerge within and between systems with autonomous capabilities. Thus, this area must be given sufficient attention in order to design and implement automated functions and co-adapt organizations, doctrine, methods, and C2 in order to gain the intended benefits and manage the risks of automated and unmanned systems.

5.5.5 Summary of Any NATO Communications/Collaborations/Interactions

The study was communicated in the planning, execution and analysis phases to HFM-247 participants, in technical meetings.

	Planning/Design	**Execution**	**Analysis**
Communication	*X*	X	*X*
Coordination			
Collaboration			

5.5.6 Future Research Needs and Plans in This Area

In connection to each theme, the research team's suggestions for further inquiry or research to be considered by the Swedish Armed Forces have been provided above.

5.5.7 Acknowledgements

Rogier Woltjer, Jörgen Bergfeldt, Peter Svenmarck, Peter Nilsson, and Björn Johansson, all of FOI, constituted the research team performing the LASSA study.

For the reference to the full report in Swedish in the form of an FOI technical report we refer to [103], and for the reference to the English executive summary in the form of an FOI memorandum to [104].

This English summary was compiled with the assistance of Kristofer Bengtsson and reviewed by Susanna Nilsson, both of FOI.

5.6 UK-1: HAT-CV&V HUMAN-AUTONOMY TEAMING – COLLABORATION, VERIFICATION AND VALIDATION

5.6.1 Brief Description

Human-Autonomy Teaming (HAT) – the creation of a mutually supportive, cooperative, collaborative partnership between the human user and advanced "intelligent" automation technology – has been recognized as the necessary strategic, human-system integration design objective for Unmanned Systems (UxS). HAT is aimed at delivering efficiently and effectively the required agile, adaptive, context sensitive, multi-mission capability,

whilst enabling meaningful and effective command and control. Concurrently, the provision of effective test and evaluation methodology for proving HAT efficacy, with verification and validation of human-system performance and effectiveness, has been identified as presenting a significant technical challenge. The aim of this TG HFM-247 UK Technical Activity is to identify HAT user requirements and develop methodologies for test and evaluation, verification and validation of HAT concepts and mission enabling technologies for UAS in joint, collaborative manned-unmanned operations. This report describes the approach and methodology developed under the UK Ministry of Defence (MoD) Defence Science and Technology Laboratory (Dstl) UAS Research and Development (R&D) Programme, and used to measure, test, compare and evaluate the risks and stressors for HAT with advanced UAS mission enabling, decision support, automation and autonomy technologies.

5.6.2 Introduction

Remote and automated systems employing unmanned and remotely operated platforms, and systems employing embedded automation and self-governing autonomous functionality, are being increasingly employed as enablers of military capability. However, it is widely recognized that in the complex, dynamic and uncertain environment of military operations, human effectiveness and HAT is needed, as an axiomatic design imperative, for autonomous systems to be assuredly safe and effective.

Prior to the advent of Artificial Intelligence (AI) and before the introduction of decision-making technology, the human commander/operator retained sole responsibility for providing cognitive decision-making capability. The commander/operator uses sensing, thinking, values, reasoning, learning, knowledge and memory, coupled with judgement, vision and imagination, shared and developed through social communication and dialogue. Cognitive capability enables human judgement to be reasonable, dependable and reliable in dealing with uncertainties and ambiguity. But it also enables humans to be innovative and creative, thereby anticipating options, contingencies, risks, opportunities and threats. This creative cognitive capability provides the essential context sensitivity, flexibility, agility and adaptability needed for decision superiority in the complex, dynamic military environment. Selection, training and discipline, coupled with delegation and supervisory operating procedures, are used to manage and mitigate the variability and inherent unreliability associated with non-deterministic human cognitive functioning and performance. Technological limitations, legal and moral constraints, and requirements for most effective human involvement, indicate that some form of human-in-the-loop control always will be required. This means that finding the right balance of human cognition and supervision of automation usage must be identified and proven to be matched to the demands and risks of specific contexts of use. Rigorous Test and Evaluation (T&E) is needed in representative and stressing operational mission environments with applicable Command and Control (C2) systems. Because of the inherent unreliability of human supervision, system safeguarding measures are needed to provide assured resilience to human performance variability and neglect. Increasing dependency on HAT for human and autonomous-system effectiveness, raises the risks of human fallibility in governing autonomous systems performance, and increases the need for robust, reliable, certifiable and trustworthy autonomous systems software. Additionally, HAT increases recognition of the requirement for built-in independent automatic systems providing safeguarding, regulation and policing of autonomous systems operations, such as automated logical management of operation policies monitoring and enforcement (e.g., Configurable Operating Model Policy for Automation and Control of Tasks (COMPACT)).

5.6.3 UK Research Programme

To address these challenging issues, and to identify requirements for autonomous systems operation and control, UK MoD Dstl has conducted a comprehensive programme of R&D on Autonomy and Mission Systems (AMS),

with over 17 years of testing autonomous systems concepts and mission enabling technologies. The scope and incremental phased progression of the MoD AMS programme elements from circa 2000 to the present, is illustrated in Table 5-3.

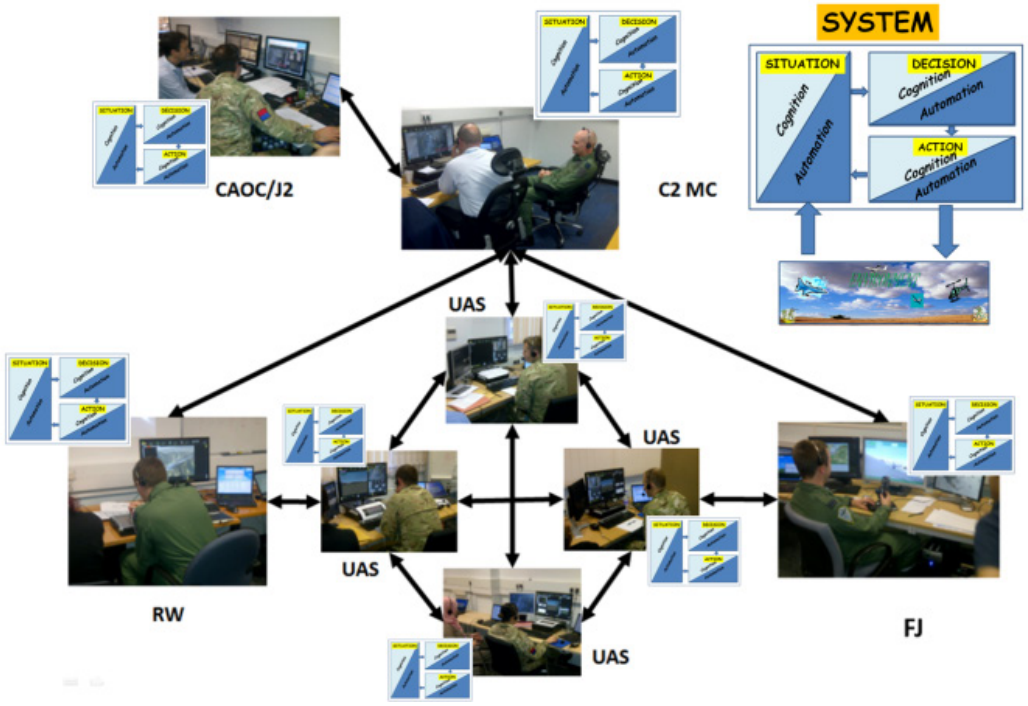
Table 5-3: UK Autonomy and Mission Systems Research Programme Progression 2000 – 2015.

INCREMENTAL INTREROPERABILITY & SYSTEM INTEGRATION		Mission Planning & Control, COGPIT, FOAEW MASC ARTD, JEDDI Vista Warrior PA	Information & Mission Management, TIEC, Decision Superiority, UAV Autonomy & Control, RTAVS, Strike Warrior PA, CWSD PA	Mission Enabling Tech, UAV Autonomy & Airspace Integration, NCSC/SID PA	DAMM, UAV Autonomy & Mission Management	Collaborative Autonomy, ABC, Adaptable Autonomy MC-MACE PA, TABM PA
ISTAR Integration	Ops			ISTAR, CAOC J2 POI	ISR Soak, ISTAR Deck, POR, NAI, AOI, Mandatory Reporting	TCPED, J2 Image Analyst, ISR requests, Image transfer, urban tele-presence
	Tech				NAI planner/ scheduler	Layered ISTAR, J2 IRL, VMF TDL, USAF UT Immersive HMI, Fused AO IRL
Air Battle Space Integration	Ops			Air C2, Tasking, ABM	COAC	Air Battle Space Conditioning
	Tech			JDOCS, ICC, OpTEAM, ATO/ACO, Fuel, Airspace, Threats, Blue Force, SAFIRE, Chat/Free text, Imagery, 3D audio comms, Speech-to-text	ICC, GARS, TacC2	
Air-Lan Integration	Ops			JTAC Overwatch, PoL, HVI, VBIED, PID, CDE, CAS, TIC, Armed Recce, JPR, CASEVAC, SoF	MML, Dismounted patrol, compound & convoy overwatch, explosion, insurgent INS activity, INS command, IED convoy strike, weapons cache, AAA	Convoy Commander & JTAC & RW UAV EO FMV control
	Tech			DESCAT, USAF BATMAN, Map/Image Mark-up, 3D audio target cueing		
Tactical Air Missions	Ops	Fast jet Interdiction Strike	UCAV LO, Deep Target Attack, LOS/BLOS, EMCOM, Mobile HVT Search Verify Attack, Rotary Wing, SH, AH	Mission Commander, Persistent strike, SEAD/DEAD, CAP, AAR, F2T2EA, TST, CDE, BDA	AUAS Package Commander, SKASC MC, P2P, ISR, CAS, TUAV, OUAV, TacP, HLZ recce, SA18, WPNS, FOB resupply	Urban, convoy overwatch, battle captain, S/MUAV, base protection, TUAV GCS IA
	Tech	MPS, moving map, IER/ICD, Auto-routing, INAS, HMDS, PNVG, SASS, TIM, PACT, KBS	TDL, PPLI, Flying Egg, Route Share, ADSS, UAV ACS, PACT L3 Agents, GMTI/EO IR/BIL, OMPS, Indivisibility HFI	TacTEAM, TDSS, Multi UAV GCS TEF, USAF Vigilant Spirit GCS, ATD/ATR, ELS, RWR, Smart Map WAS	Tactics Library, UAS Scheduler, TEF Goal based planner, Optimiser, ITRPs, IRL report HMI, image filter, MC MTEF GCS tasking, PMM, UAV/FJ/RW status, integrated chat, free text, UAV FMV control	WKR trinity C2E multi-TUAV GCS, EO FMV, IRL, Hybrid architecture, SUAV TEF GCS, BC HMI, Policy Management, SASS, TIM, CMADS
MOP/MOE		Workload, IPME, SWAT, TLX, DRAWS, Conjoint scaling, SA, SAINT, SART, Electrophysiology	HVT S/V/A workload, shoot times, IE data rate, Auto Sufficiency, Viability, Targets, Threats, Tasks, Tactics, CMDM Decision strength, S/E/T, Reliability, Usability, Confidence	Mission objectives achieved, ToT, PMS, AP, Collaboration Coefficiency, Teamwork, Task Performance, REMDAER, 4Ts, Decision/ Action load, Reward/ Effort Efficiency, Electrophysiology heart rate variability	Imaging, tool usability, utility, reliability, confidence, trust, TLX, MEC scoreboard	CAPTEAM, Conflict Adaptation, USAF TBM, AS TBM

Table 5-3 summarizes the progressive interoperability and systems integration testing of mission enabling technologies, automation and autonomy demonstrating a widening area of influence and military relevance. The scope for autonomous systems control has increased to encompass Intelligence, Surveillance and Reconnaissance (ISR) and C2 at strategic, operational and tactical Mission Management levels (C2-MM).

5.6.4 Test and Evaluation Requirements

Requirements for T&E metrics have changed as R&D on Collaborative and Adaptable Autonomy, including Manned-Unmanned Teaming (MUMT) and HAT, have become prioritized. Applicable T&E Measures of Performance and Effectiveness (MoP/MoE) identified indicate a progression from focussing on individual human performance metrics of workload and Situational Awareness (SA), through measures of decision making and system performance, to higher-level metrics for adaptability proficiency, and team-based metrics for collaboration and teamwork. Figure 5-15 summarizes the guiding considerations for the programme, and illustrates the scope of control covering C2 levels, with the testing of human effectiveness in dynamic missions decision-making adaptability focussing on HAT cognition/automation balance. This reflects the recommended core components of the US DoD 2012 Defense Science Board (DSB) Framework for Autonomous Systems development, test and evaluation, namely cognitive echelons, mission timelines and adaptive capacity trade spaces [105].



WHY?

Level of Proof
- Proof of concept
- Functional purpose
- Technology development
- System verification & validation
- Certification

Scientific Robustness
- Validity
- Reliability
- Sensitivity
- Discriminability
- Diagnosticity

Standards
- National/International
- HE/Aircrew system design
- NATO/ASCC

WHAT?

System/Technology Readiness Level
- Early concept development (Low TRL/SRL Level 1-3)
- Advanced system technology integration, demonstration (TDP SRL/TRL 3-5)
- Mature systems capability field/flight test and evaluation (CCD SRL/TRL 5-7)

Level of System
- CONUSE and Doctrine
- Systems Design
- Functions Design

HOW?

Constraints
- CONOPS: LoAC, ROE, CDE, BDA
- Environment: Weather, Geographic
- Time – Mission, run
- System Technical Limitations
  - Realism/Representativeness
  - Sensor models, Communications
  - Reliability, robustness
- Measurement

Enablers
- Resources, Support
- System tools
- Network communications
- C2 architecture, Mission command
- CONOPS: Plans, Tasks, TTPs

Scenario
- Scenario – SAG
- Representative missions
- Vignettes, Use cases
- Targets, Threats, Tactics, Tasks
- Planned, unplanned, events/decisions

Test Environment
- SE
- Live
- Live, virtual, constructive

Test Design
- Independent variables
  - Levels of autonomy
  - Networking
- Dependent variables
  - MOE/MOP
  - Objective measures
  - Subjective measures
- Training

Figure 5-15: UK C2-MM Cognition/Automation Trade Space – Why, What and How?

The DSB 2012 report identifies the challenges for T&E of autonomous systems. Currently, T&E processes are used to provide full-path regression testing, seeking to exhaustively validate every individual requirement. Autonomous systems T&E is challenging because autonomy software interacts with a dynamic environment,

often coupled with machine learning, operating in a non-deterministic, unpredictable manner. Hybrid system solutions involve a mix of deterministic and non-deterministic algorithms, as well as human decision making. So, with both human effectiveness and HAT as axiomatic design imperatives for military relevance, T&E must be designed to be applicable to the uncertainties in both the human's and the autonomous system's deterministic and non-deterministic decision making and behaviors. This report builds on a 2015 UAS T&E presentation to the Royal Aeronautical Society [106], with recent research on HAT concepts and metrics added.

5.6.5 SE and LVC Testing

The UK approach to development and testing of autonomy concepts and technologies uses a combination of laboratory-based simulation Synthetic Environments (SE) and Live-Virtual Constructive (LVC) trials. Early examples are illustrated in Figure 5-16. SE trials provide a rich and controllable context for innovation and stressing proof-of-concept, enabling technical risk reduction and human effectiveness testing. UAS were operated by qualified experienced military personnel, performing operationally realistic, joint tactical missions and tasks, with representative C2 and ISR environments.

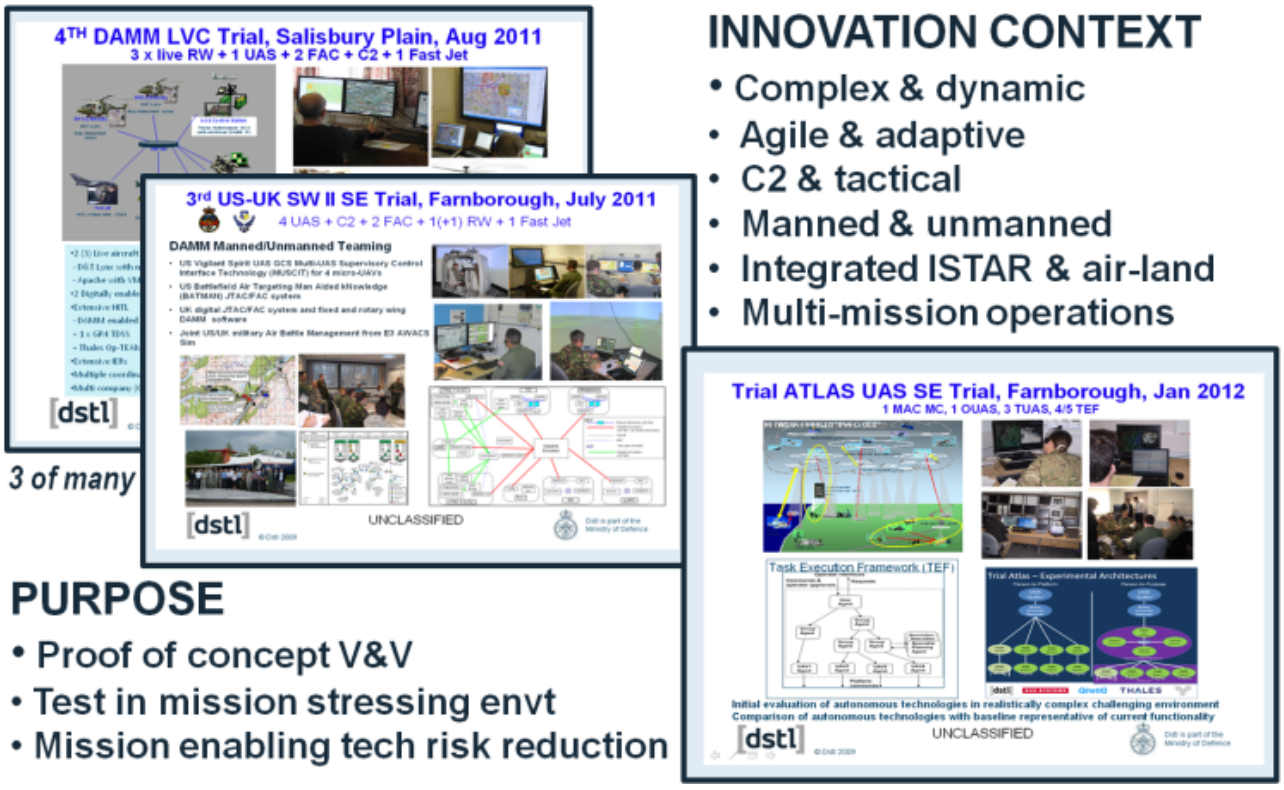


Figure 5-16: UAS LVC and SE Research Trials.

Autonomy testing needs to use endorsed military scenarios and validated uses cases, with a networked force mix of manned and unmanned platforms, including representative air, land and maritime force elements and assets. Stressing events, decision points and independent variables are used to test adaptive capacity. Adaptive capacity variables tested include constraints, enablers, resources, altered situations, decision types and adjustment strategies (Figure 5-17).

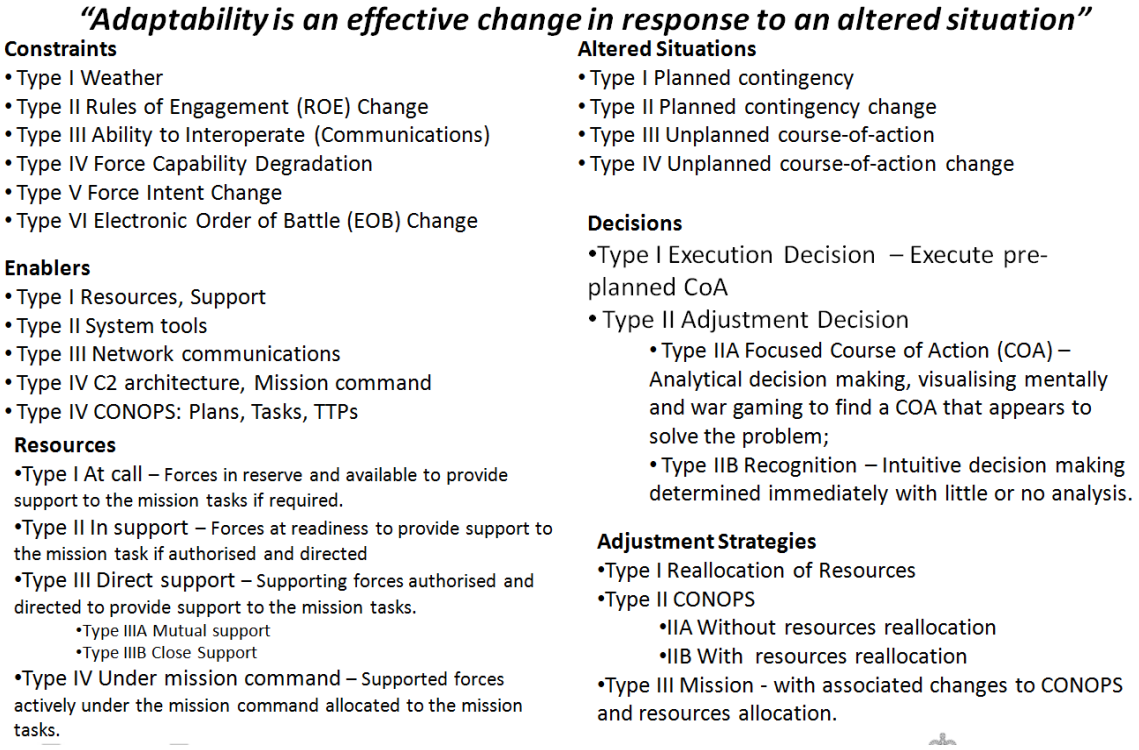


Figure 5-17: Adaptive Capacity Variables.

5.6.6 Test Design

The key human-system effectiveness and adaptability proficiency goals of UK autonomy research with HAT-CV&V, demand scientifically robust and validated human-system performance testing and assessment methods. Applicable methods need to be tailored to customer/stakeholder requirements and focused to address specific research priorities. Test methods are needed that are designed to achieve the levels of proof required to support evidence-based decision making in UK MoD Defence Equipment procurement. Selection of test methods involves balancing requirements for innovation and demonstration (e.g., use case testing), compared with the need for robust performance-based trade space analysis, valuing discrimination power and optimization (e.g., multivariate performance testing). Figure 5-18 illustrates the distinction between innovation and discrimination test methods.

5.6.7 Critical Decision Methodology

Underpinning the test methodology, and providing the required human effectiveness centric focus, Dstl has developed a cognitive capability testing approach, based on dynamic Mission Critical Decision Making (MCDM) methodology. MCDM was initially developed to investigate requirements for Dynamic Air Mission Management (DAMM). MCDM focuses the locus of testing of Course of Action (CoA) adjustment responses to dynamic mission critical events. MCDM employs objective, task analysis and effects-based MoE/MoP, coupled with subjective decision-based metrics for estimation of human and mission effectiveness (Collaborative Adaptability Proficiency Test Evaluation Assessment Methodology (CAPTEAM)). Essentially, the aim is to capture the agility (speed) and adaptability (quality) of mission commander/operator decision making in dynamic mission timeline context as illustrated in Figure 5-19.

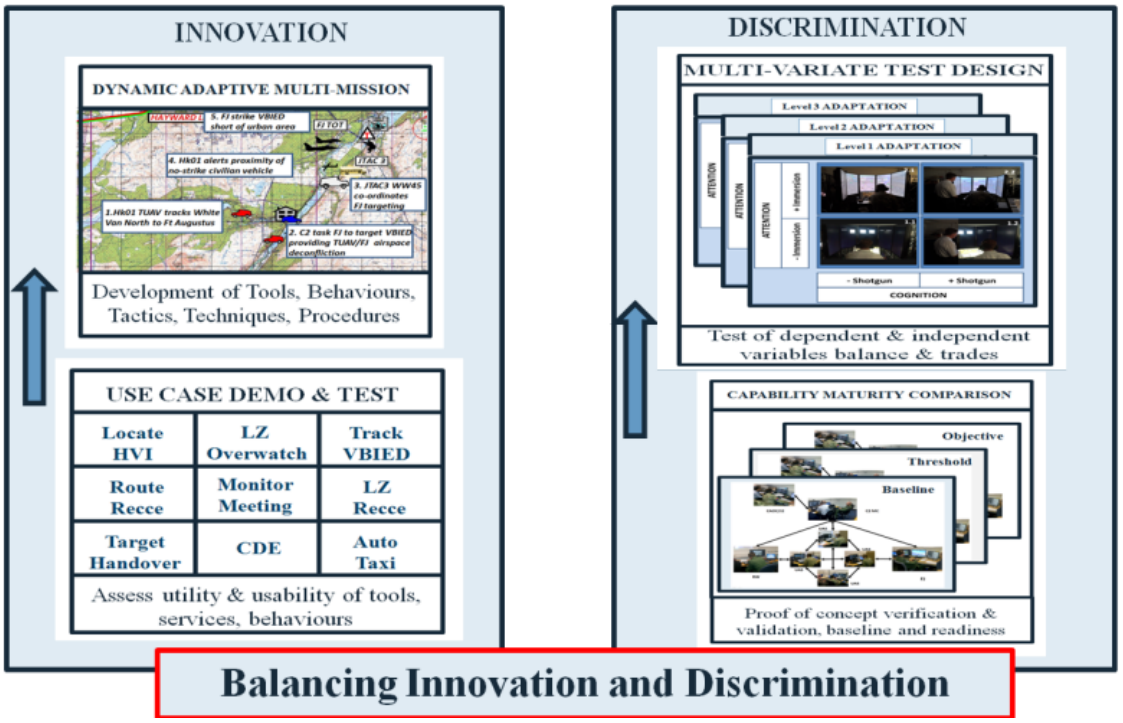


Figure 5-18: Applicable Test Methods.

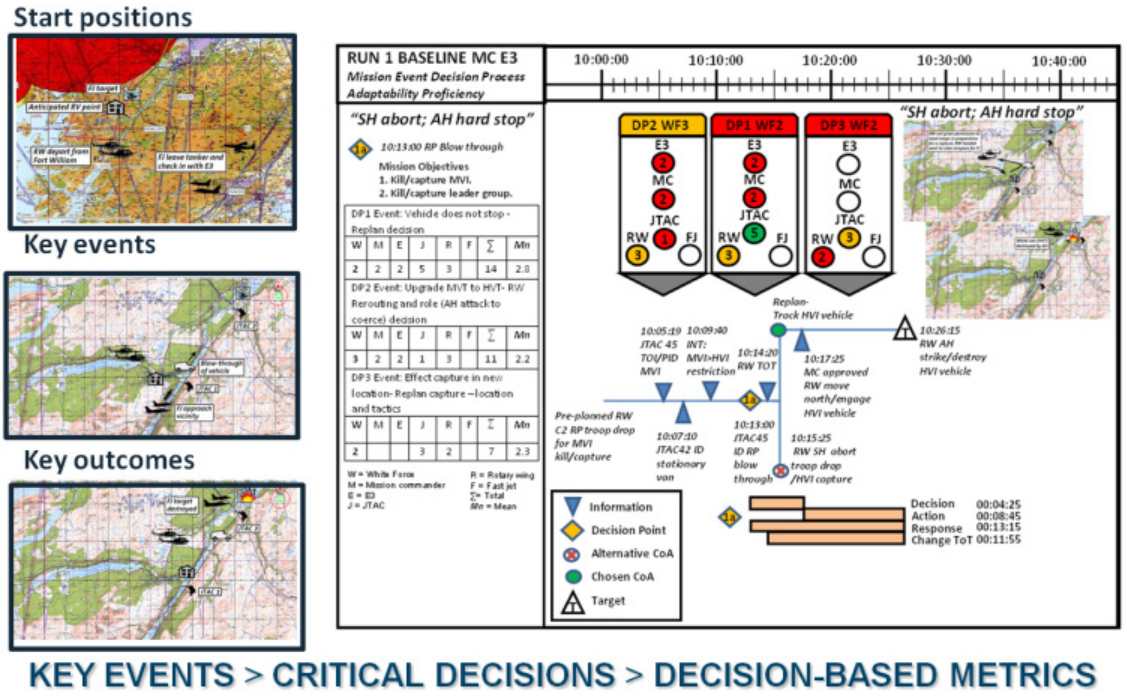


Figure 5-19: Dstl MCDM Methodology.

Subsequently, under the UK AMS Research Programme, the MCDM methodology was further developed to measure collaborative adaptability proficiency with autonomous systems concepts and technologies. This has included investigating C2-MM decision making by varying and controlling demands for levels of conflict resolution (Figure 5-20), and by observing collaborative mitigation/adaptation responses, considered in terms of coordination (de-conflicting acts), cooperation (de-conflicting means) and collaboration (de-conflicting goals).

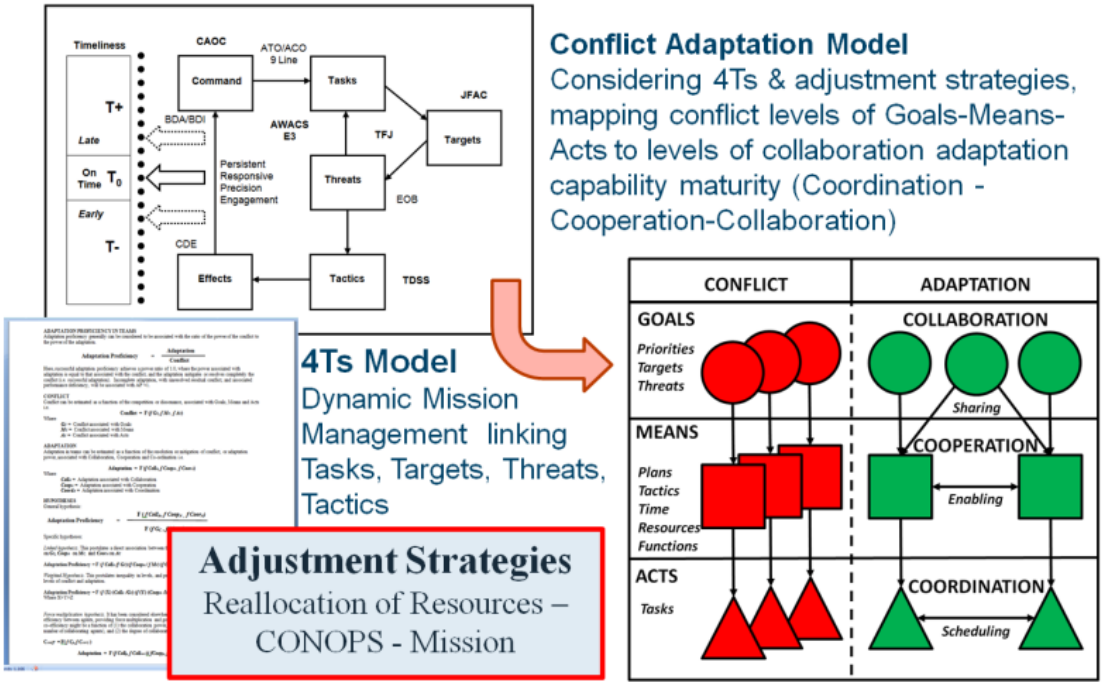


Figure 5-20: Conflict Adaptation.

5.6.8 CAPTEAM Metrics

The MCDM approach is coupled with the Dstl CAPTEAM. Dstl MCDM and CAPTEAM have been reported previously through the 2012 NATO TG HFM-170 [107]. CAPTEAM is intended to provide full-spectrum task and team-based metrics for collaborative adaptability proficiency. CAPTEAM includes models, methods, subjective assessment protocols and metrics for participant taskwork and observer assessed teamwork, including tool and technical system usability, utility, confidence and reliability. Figure 5-21 illustrates the Participant (P) and Observer (O) protocol components (Likert 7-point, Low-High, anchored rating scales). Figure 5-22 shows the provenance of the individual components build.

Figure 5-23 highlights the CAPTEAM results for Probability of Mission Success (PMS) and Adaptability Proficiency (AP) in a controlled comparison (discrimination) of network and autonomy independent variables in A&MM 2012 Trial Caucasus. Figure 5-24 shows the results of analysis of CAPTEAM component ratings using Principal Coordinates Analysis (PCA). Inter-correlations indicate the degree of association of CAPTEAM components with estimates of Probability of Mission Success (PMS). PCA differentiates components associated with taskwork and teamwork, and linked to effort (workload) and reward/benefit (e.g., situation awareness, decision quality). Workload components show a relatively weak correlation with PMS. This contrasts with the relatively high correlations obtained for decision quality, collaboration and adaptability proficiency.

PARTICIPANT PROTOCOL RATING SCALE INTERPRETATION

LOW ANCHORS	DIMENSION	HIGH ANCHORS
	Low1 2 3 4 5 6 7High	
	WORKLOAD	
Slow/Leisurely/No time pressure	**WL Time Pressure**	*Rushed/Rapid/Frantic*
Very little/Extremely easy	**WL Mental Effort**	*Extremely hard/Stretched*
Relaxed/Placid/Tranquil/Calm	**WL Stress**	*Anxious/Worried/Up tight/Harassed*
Light/Quiet/Unpressured	**Team Workload**	*Heavy/Busy/Pressured*
	REPLAN TASK LOAD	
Forgiving/Simple/Easy	**Replan Decision** Recognise–Evaluate-Mitigate	*Difficult/Demanding/Complex/Exacting*
Forgiving/Simple/Easy	**Replan Action** Disseminate–Acknowledge–Execute-Report	*Difficult/Demanding/Complex/Exacting*
	SITUATION AWARENESS	
Stable/Simple/Fixed	**SA Demand on Attentional Resources**	*Unstable/Complex/Variable*
Relaxed/Inattentive/Spare Capacity/Singular	**SA Supply of Attentional Resources**	*Alert/Concentrated/Full capacity/Divided*
Uninformative/Meaningless/Unfamiliar	**SA Understanding**	*Informative/Meaningful/Familiar*
	DECISION QUALITY	
Indecisive/ Doubtful/Guess	**DQ Confidence**	*Decisive /Confident /Obvious*
Dangerous/Vulnerable/Risky	**DQ Survivability**	*Safe/Unthreatening/Secure*
Ineffective/Un-useful/Unproductive	**DQ Effectiveness**	*Effective/Capable/Useful*
Behind/Late/Pressurised	**DQ Timeliness**	*Ahead/On-time/In control*
	PERFORMANCE	
Unsatisfactory/Unacceptable/Failure	**Task Performance**	*Perfect/Successful/Satisfied*
Useless/Complicated/Difficult	**Tools Utility**	*Easy/Intuitive/Effective*
No backup plans/ Insensitive/Unresponsive	**Adaptability Proficiency**	*Sensitive/Responsive/Timely effective backup plans*
Fails to meet any mission objectives/0%	**Probability of Mission Success**	*100%/Successfully achieved all mission objectives*

OBSERVER PROTOCOL RATING SCALE INTERPRETATION

LOW ANCHORS	DIMENSION	HIGH ANCHORS
	Low1 2 3 4 5 6 7High	
	DECISION QUALITY	
Dangerous/Vulnerable/Risky	DQ Survivability	*Safe/Unthreatening/Secure*
Ineffective/Useless/Unproductive	DQ Effectiveness	*Effective/Capable/Useful*
Behind/Late/Pressurised	DQ Timeliness	*Ahead/On-time/In control*
	TEAMWORK	
Silent/Unclear/Confused/Slow/Uninformative	Communication	*Clear/Timely/Coherent/Concise/Rapid/Informative*
Uninformative/Meaningless/Unfamiliar	Shared SA	*Informative/Meaningful/Familiar*
Indecisive/Unassertive/Confused/Uncommunicative	Leadership	*Commanding/Directing/Guiding/Initiating*
Ignoring/Hindering/Blocking/Criticising/Conflicting	Support	*Monitoring/Advising/Correcting/Assisting*
Light/Quiet/Unpressured	Team Workload	*Heavy/Busy/Pressured*
	PERFORMANCE	
Unsatisfactory/Unacceptable/Failure	Task Performance	*Perfect/Successful/Satisfied*
Separate/Independent/Divided/Conflicting	Collaboration	*Joint/Shared/Coordinated/Cooperating*
Powerless/Weak/Irrelevant/Not Involved	Influence Power	*Influential/Powerful/Forceful/Decisive/Critical*
No backup plans/ Insensitive/Unresponsive	Adaptability Proficiency	*Sensitive/Responsive/Timely effective backup plans*
Fails to achieve any mission objective/0%	Probability of Mission Success	*100%/ All mission objectives successfully achieved*

Figure 5-21: CAPTEAM Protocol Components.

FACTOR	COMPONENT	P/O	SOURCE
WL-Workload	WL Time Pressure	P	USAF AFRL SWAT, Reid 1988. ASCC ADV PUB 61/116/17 Operator Capability Analysis, A77-80, 1997. TTCP HUM TP7 WL Metric of choice.
	WL Mental Effort	P	
	WL Stress	P	
Replan Load	Decision(Recognise Evaluate Mitigate)	P	DSTL/AFRL REMDAER C^{2}OODA , US-UK Strike Warrior II 3rd Joint DAMM Trial 2011
	Action(DisseminateAcknowledge Execute Report)	P	
SA-Situational Awareness	SA Demand	P	RAF IAM SART, Taylor 1990. ASCC ADV PUB 61/116/17 Operator Capability Analysis, A73-76, 1997. TTCP HUM TP7 SA Metric of choice.
	SA Supply	P	
	SA Understanding	P	
DQ – Decision Quality	DQ Confidence	P	DSTL TIEC Test Methodology, 2005. DUE Decision Utility Estimate Metrics.
	DQ Survivability	P,O	
	DQ Effectiveness	P,O	
	DQ Timeliness	P,O	
Teamwork	Collaboration	O	DSTL/AFRL/DSTO Teamwork Metrics. US-UK Strike Warrior II, 2nd Joint Trial 2010. Protocol included Coordination, Cooperation. Participant (P) and Observer (O) protocols rationalised for DAMM ABTC Technology Insertion Trial, RAF Waddington, July 2011.
	Communication	O	
	Shared SA	O	
	Leadership	O	
	Support	O	
	Team workload	O	
	Influence Power	O	
Performance	Task Performance	P,O	DSTL/AFRL/DSTO White Force Adaptability metric, US-UK Strike Warrior II – 2nd Joint Trial 2010
	Adaptability Proficiency	P,O	
	Prob. Mission Success	P,O	
Tools	Tools Usability	P	DSTL/AFRL US-UK Strike Warrior II 2nd Joint DAMM Trial 2010, Tools Usability metrics
	Tools Utility	P	
Technical System	Reliability	P	DSTL System Confidence Protocol, US-UK Project Churchill UCAV Trial March 2007.
	Confidence	P	
	Usability	P	

Figure 5-22: CAPTEAM Build Provenance.

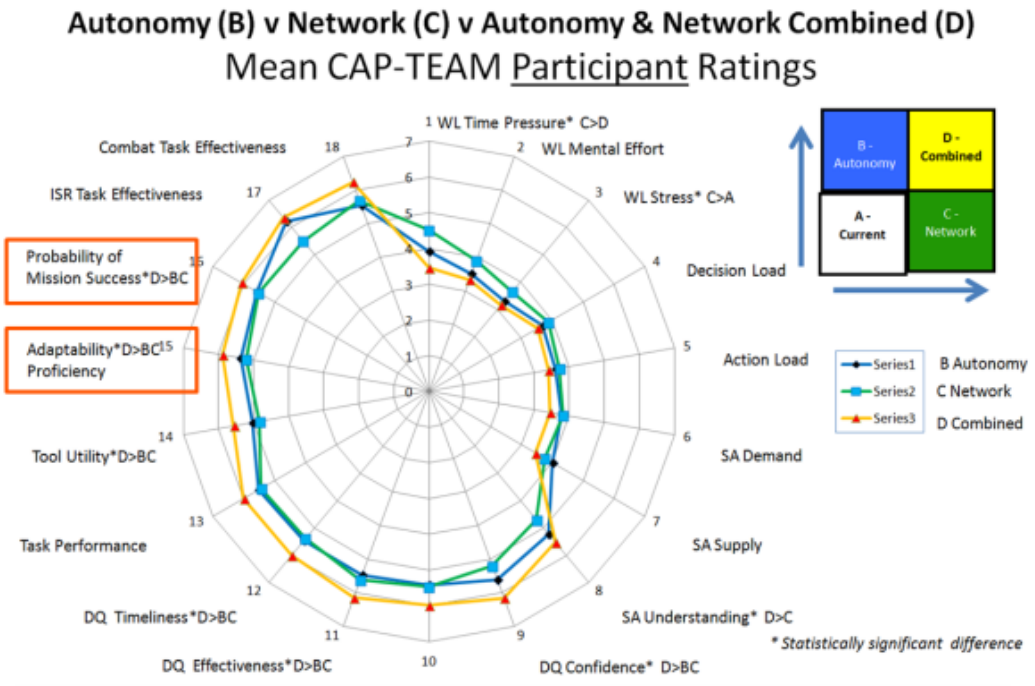


Figure 5-23: A&MM Trial Caucasus 2012.

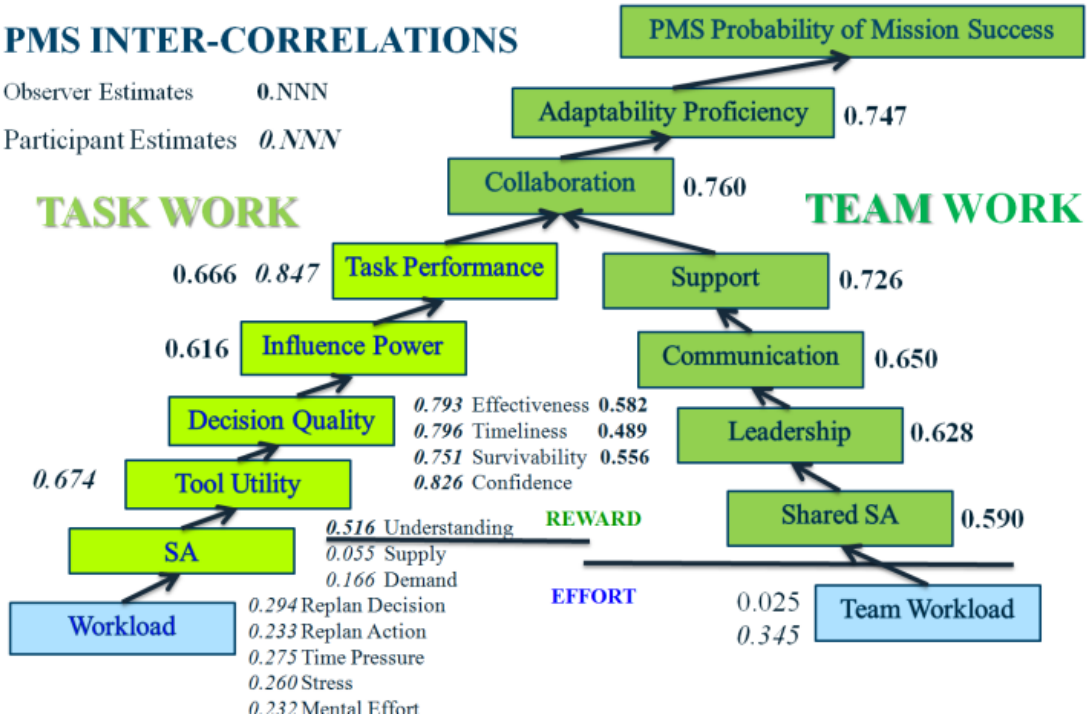


Figure 5-24: Inter-Correlations with PMS.

5.6.9 Performance Benchmarks

A benefit from re-using MCDM/CAPTEAM methodology for Autonomous Systems Research T&E consistently over time has been to enable a set of recognized benchmarks to be established. These benchmarks help frame the assessment context, and act as validated performance standards for comparison, gauging the relative strength of collaborative adaptability proficiency in development prototypes, providing estimates of human, technical and system readiness. Figure 5-25 illustrates the application CAPTEAM benchmarks for AP and PMS. The benchmarks are the means of ratings for AP and PMS obtained by CAPTEAM from Trial Caucasus Configuration D (High) and US-UK Strike Warrior III (High and Low). These benchmarks were chosen for their relevance, representativeness and statistical robustness (large data sample sizes). Here, these benchmarks are compared with the CAPTEAM results for UAS automation and decision support tools supporting mission tasks tested on a prototype high integrity avionics rig. Shortfalls indicate capacity availability for raising AP and PMS.

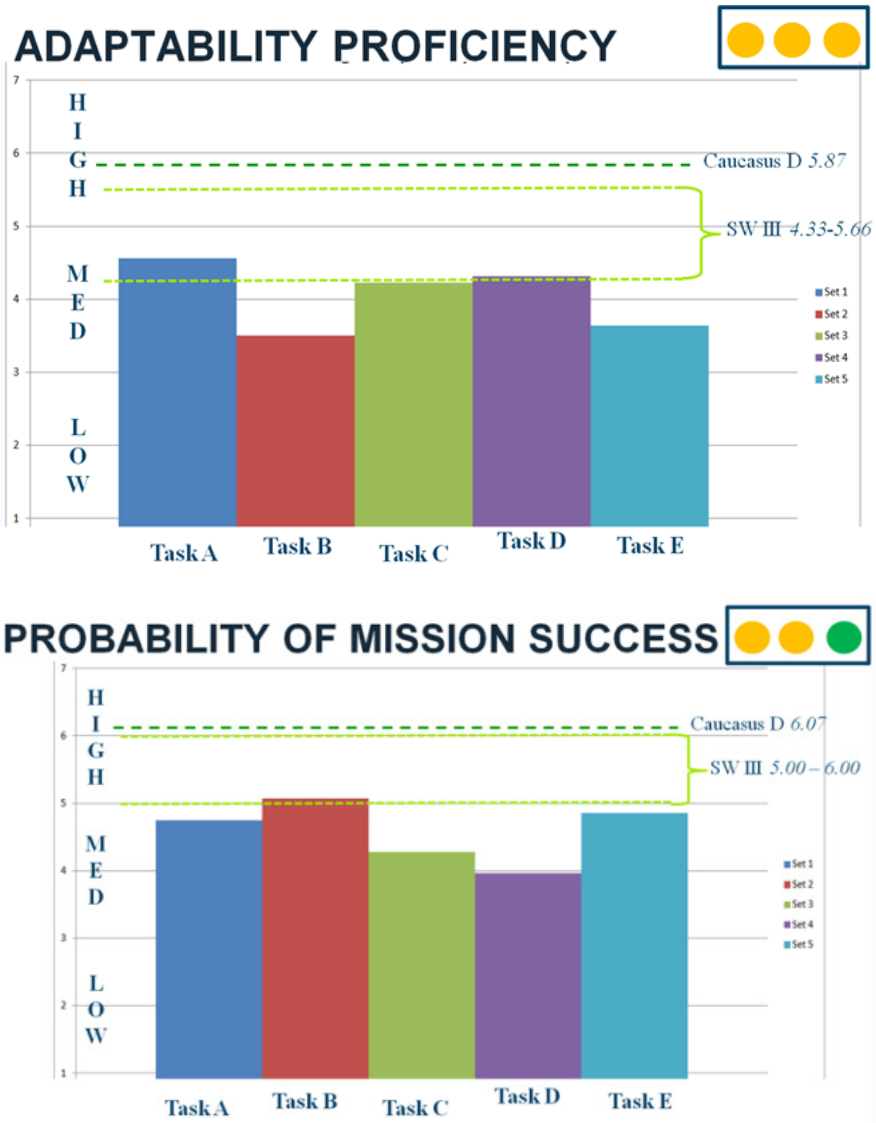


Figure 5-25: Benchmarks Estimating Readiness.

5.6.10 Collaborative Adaptable Autonomy

Recent UK MoD Autonomy Research on enabling HAT through programmes on Collaborative and Adaptable Autonomy, have focused on the development of technologies and interoperability procedures for MUMT, and on the systems for managing variable autonomy through automated logical Policy Management (PolMan), using COMPACT. (Figure 5-26).

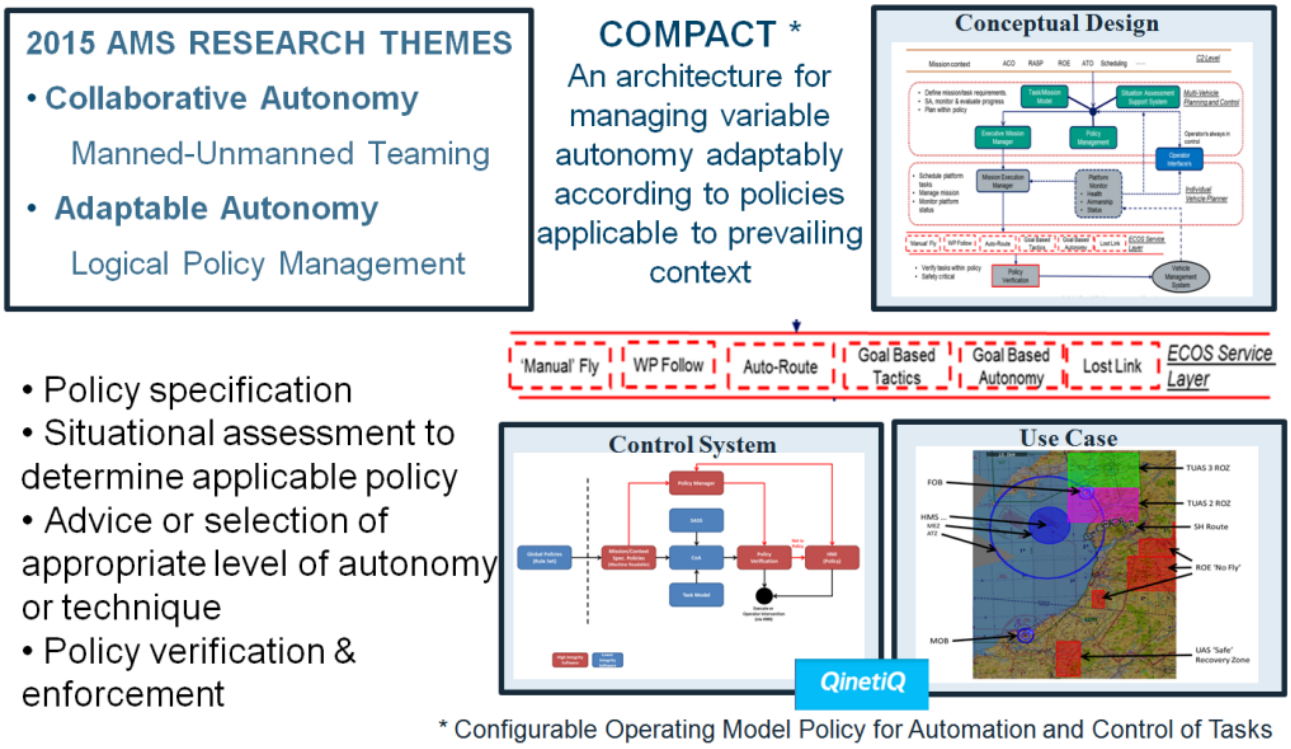


Figure 5-26: COMPACT Enabling Human-Autonomy Teaming.

To support testing MUMT and COMPACT concepts and technologies in SE and LVC trials, analytical work has focused on developing improved models and metrics for HAT collaboration, verification and validation with strengthening of autonomy component assessments. CAPTEAM metrics were originally designed to assess human effectiveness with mission enabling technologies viewed primarily as tools and decision-making aids. Consequently, the evaluation of autonomy technologies was initially considered in terms of their utility as tools for human use, rather than as potentially interacting agents, Electronic Crew Members, or "teammates". Original CAPTEAM Taskwork metrics were derived from models of human cognition and performance (e.g., workload, SA, decision making). Similarly, CAPTEAM Teamwork metrics were derived from models of human teamwork (e.g., Crew Resource Management (CRM)). So, initially, alongside Task and Teamwork metrics, autonomous functions and behaviors were assessed as systems and tools, judging performance and effectiveness in terms of utility, reliability, confidence and usability. Now, with developments in AI enabling more collaborative, adaptable and adaptive autonomy concepts and technologies, the increasing emphasis on enabling HAT means that the adequacy of the tools-based approach to testing needs to be reviewed. Additional socio-technical models and metrics need to be considered for measuring autonomous systems performance, such as reliability, resilience and brittleness, in dynamic mission contexts requiring HAT collaboration. This should include the consequences

of requirements for HAT collaboration, arising from developments in machine learning, mixed-initiative operations, dynamic function allocation, delegated and joint decision making, and complex operator-autonomy bi-lateral interaction and dialogue. New models and metrics are needed for assessment of autonomous systems and HAT, with improved sensitivity, discrimination and diagnostic power. They need to be capable of assessing the efficiency and effectiveness of commander/operator-autonomous systems balance and teaming. They need to better enable the identification and mitigation of the risks of autonomy and HAT, and ultimately to improve the use of autonomy and increase HAT capability maturity.

5.6.11 HAT Models and Metrics

Analysis of the human and autonomy requirements for modelling and measuring HAT can be informed in part by the structure of human teamwork. CAPTEAM represents human teamwork by discriminating between human taskwork and human teamwork components. For a more complete description of HAT, consideration of the consequences of adding autonomy to the force mix leads to recognition of the need for equivalent components to account for autonomy taskwork and teamwork, including both autonomy-autonomy and human-autonomy teaming. This formulation is represented in Figure 5-27. Logically the locus of the teaming effect is unsurprisingly collaboration, which the CAPTEAM inter-correlations (Figure 5-24) show to be highly correlated with mission success (PMS). Additional components to CAPTEAM that might contribute to a wider HAT subjective assessment protocol (HATTEAM?) are shown in Table 5-4. These are nominally distinguished as capabilities and enablers. For assessment purposes, significantly contributing components need to be characteristic and observable; measurable, sensitive and discriminating; and logical, meaningful and evidential.

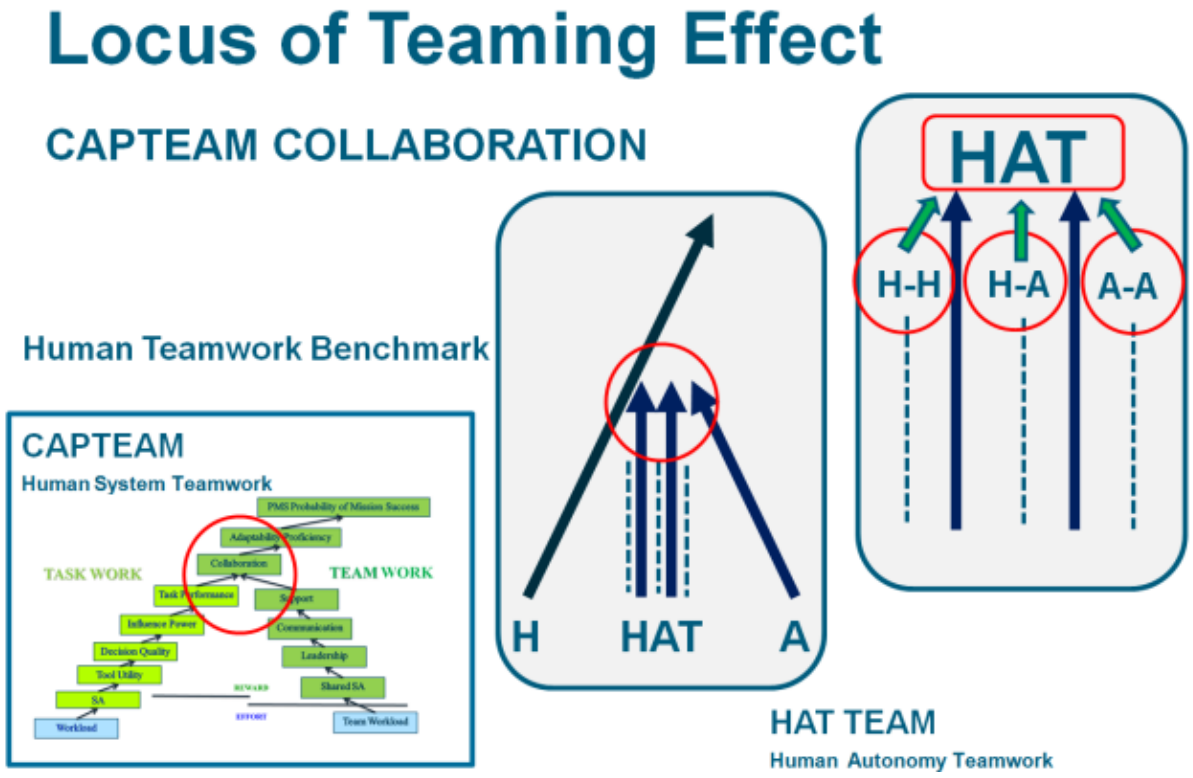


Figure 5-27: Structure of HAT.

Table 5-4: Capabilities and Enablers of HAT.

	Human Taskwork	H-H Teamwork	H-A Teamwork	A-A Teamwork	Auto Taskwork
CAPABILITY	EFFECTIVE	EFFECTIVE	EFFECTIVE	EFFECTIVE	EFFECTIVE
	ADAPTABILITY	ADAPTABILITY	ADAPTABILITY	ADAPTABILITY	ADAPTABILITY
	AGILITY	AGILITY	AGILITY	AGILITY	AGILITY
	SAFETY	SAFETY	SAFETY	SAFETY	SAFETY
			RESILIENCE	RESILIENCE	RESILIENCE
				PERSISTENCE	PERSISTENCE
ENABLERS Characteristic Observable Measureable Sensitive Discriminable Logical Meaningful Evidential		Collaboration	Collaboration	Collaboration	
	Performance	Performance	Consistency	Consistency	Consistency
		Support	Configurable	Configurable	Configurable
		Communication	Negotiable	Transparency	Transparency
	Decision quality	Decision quality	Decision quality	Trustworthiness	Provenance
			Usability	Utility	Utility
			Reliability	Reliability	Reliability
	Influence power	Leadership	Leadership	Conformance	Conformance
	SA	Shared SA	Sensitivity	Sensitivity	Sensitivity
	Workload	Team workload	Scalability	Scalability	Scalability

Selection of assessment components of autonomy taskwork seems particularly problematic since much of the detailed functioning of algorithms lacks observability at most commander/operator interfaces. This is reflected in common need for explanation and increased transparency at autonomous systems user interfaces. However, recent work under MoD ASUR Project SATLID/SATLAOP has investigated improving understanding of the requirements for trustworthiness in software, based on Publicly Available Specification 754 Software Certification. The results of this work help guide selection of components of trustworthiness to include safety, reliability, availability, resilience and security components. With the addition of components for dependability and predictability, based on human factors literature on trust, Dstl have developed and tested both a single and a multi-dimensional subjective rating scale protocol for estimating autonomy taskwork trustworthiness. The more mature multi-dimensional rating scale, with dimension definitions and anchors, is shown in Table 5-5.

Concurrently, to help guide MoD trials in the assessments of autonomy teaming dimensions (human-autonomy and autonomy-autonomy), Dstl have proposed, developed and tested a model with metrics for assessing HAT capability maturity. The Dstl HAT Capability Maturity Model (CMM) approach is based on the 1980s software CMM work, originating from Carnegie Mellon University [108], with consideration of properties of later CMM derivatives, including more people-based dimensions (Systems Engineering, Usability, Organization, People, Team Process). The Dstl HAT CMM model has seven levels so as to be compatible for integration with CAPTEAM metrics. The levels progress from Level 0-Not Performed to Level 6-Adaptive, passing through Level 1-Initial, Level 2-Recognized, Level 3-Defined, Level 4-Managed, and Level 5-Optimizing. The seven levels of HAT CMM are each discretely defined, and differentiated in terms of goals, processes, and behaviors (Table 5-6).

Table 5-5: Dstl Trustworthiness Assessment Protocol – Dimensions and Anchors.

TRUSTWORTHINESS ANCHORS		
Low Anchors	**DIMENSION**	**High Anchors**
	Low 1 – 2 – 3 – 4 – 5 – 6 – High 7	
Unreliable; Uncertain; Inconsistent	**Reliability** The ability of the system to operate on missions, perform tasks and deliver effects as specified	Reliable; Certain; Consistent
Undependable; Fickle; Defective	**Dependability** The ability of the system to be relied upon to operate on missions, perform tasks and deliver effects as specified	Dependable; steady; loyal; faithful; responsible; unfailing
Unpredictable; Unlikely; Unexpected	**Predictability** The ability of the system to respond to events and to operate, perform and deliver effects consistently and reliably as planned and anticipated	Predictable; Likely; Expected
Unavailable; Unattainable; Unready	**Availability** The ability of the system to operate on missions, perform tasks, and deliver effects when requested	Available; Attainable; Unready
Brittle; Weak; Slow	**Resilience** The ability of the system to transform, renew and recover in timely response to events	Resilient; Robust; Agile
Unsafe; Unprotected; Unstable	**Safety** The ability of the system to operate without harmful states	Safe; Protected; Stable
Unsecure; Vulnerable; Risky	**Security** The ability of the system to remain protected against accidental or deliberate attacks	Secure; Protected; Assured

Table 5-6: Dstl CAPTEAM HAT Capability Maturity Model Rating Scale.

LOW	DSTL CAPTEAM HAT CMM 1-7 LIKERT RATING SCALE					HIGH
1	2	3	4	5	6	7
LEVEL 0 Not Performed	LEVEL 1 Initial	LEVEL 2 Recognised	LEVEL 3 Defined	LEVEL 4 Managed	LEVEL 5 Optimising	LEVEL 6 Adaptive
"...ZZZ..." "...Zzzz..."	"....Hey!" "...Hmm..."	"...Wow!!!" "...What the..!?"	"...Port?" "Nah,Starboard!"	"Clear Port?" "Yep! Clear Port!!"	"Clear Starboard!" "Clear Port!"	"All Clear!" "All Clear!"
GOALS Maintaining independence & autonomy **PROCESSES** Independent awareness, motivation & control. Separate, individuated OODA & ADAA decision making operations. Independent performance of functions, tasks, activities & capability objectives. **BEHAVIOURS** Discrete, disconnected, opaque, non-communicative, unsocial. Neglect. No interactions & information exchanges. Potentially conflicting & competing activities & objectives	**GOALS** Initiating communication **PROCESSES** Establishing communication of team awareness, connecting early OODA & ADAA input operations. Monitoring responses. **BEHAVIOURS** Ad hoc, sometimes chaotic, interactions, information exchanges , direction & support. Unplanned & unpredictable reactive responses , interactions, exchanges, direction & support. Slow, inefficient & ineffective performance	**GOALS** Recognising common ground **PROCESSES** Detecting, recognising & reproducing teaming patterns. Focusing OODA/ADAA decision operations & response selection. **BEHAVIOURS** Repeated patterns of interactions, information exchanges, direction & support. Consistent similarities & differences in performance. Error detection	**GOALS** Defining requirements **PROCESSES** Organisation of team resources, competencies, capabilities, roles & responsibilities. Analysis & definition of team processes, interactions, defining working agreements, interoperability, information exchanges, direction & support. **BEHAVIOURS** Monitoring & quantification of performance & errors. Plans, procedures, tasks, tactics & techniques. Performance standards, MoE/MoP, benchmarks, targets. Error metrics analysis.	**GOALS** Managing performance **PROCESSES** Control of team processes & performance outcomes using quantitative methods. Exercising working agreements. Planned & predictable control of safety, efficiency, timeliness & effectiveness of tasks & effects delivery. **BEHAVIOURS** Coordination. Dialogue & agreement. Systematic planned performance delivery, with error prediction, detection, mitigation & reduction.	**GOALS** Optimising performance **PROCESSES** Negotiation. Dynamic, anticipatory plan adjustment. **BEHAVIOURS** Cooperation. Neglect resilience. Fast, efficient, effective performance. Continuously improving capability & performance. Dynamic error prevention.	**GOALS** Adaptive performance **PROCESSES** Dynamic, context sensitive change detection & performance management. Dynamic optimised role, function & task allocation, Dynamic adjusted mixed initiative, collective leadership & mutual support. Machine learning. **BEHAVIOURS** Collaboration. Agile, adaptable, adaptive & resilient capability. Learning transfer.

Both the Trustworthiness protocol and the HAT CMM model have been tested in recent MoD Autonomy Research Programme SE and LVC trials. The results provide encouraging evidence for the validity and usability of these metrics for the assessment of HAT performance. Figure 5-28 concerns the design and results of the UK MoD Wildcat ISTAR Teaming for Strike (WITS) SE Trial on MUMT conducted at QinetiQ Farnborough in April 2017. The trial plan involved a progressive introduction of MUMT enabling interoperability capabilities, with rotorcraft and UAV collaborating elements, spanning a series of six trial runs with increasing complexity. Military SME operator participants provided subjective estimates of task performance, trustworthiness and HAT capability maturity for each run. In this trial, both Trustworthiness and Capability Maturity were presented as single rating dimensions. The means of the estimates closely matched objective measures of performance, and showed consistent evidence of increasing performance, trustworthiness and maturity as the trial runs progressed, indicating the validity and veracity of the metrics.

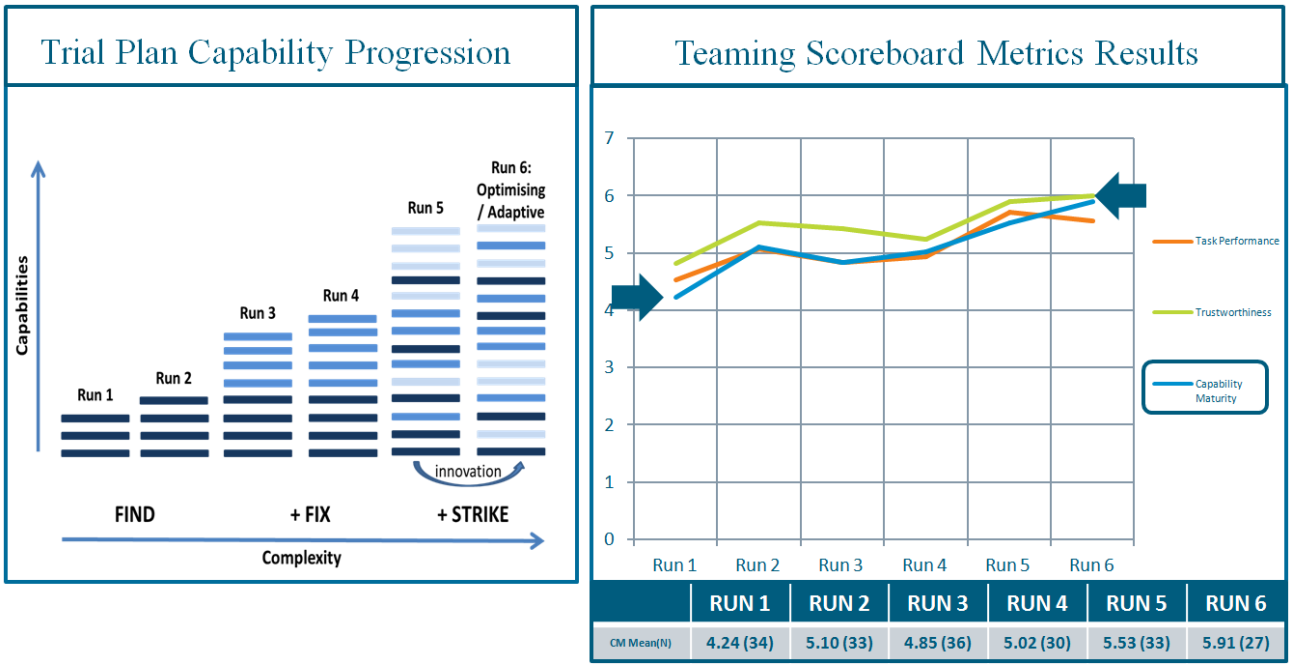


Figure 5-28: Results of Teaming Metrics for WITS MUMT SE Trial.

Subsequently, the multi-dimensional Trustworthiness Protocol was tested by application in the C2 Autonomy Trial at AFRL Dayton, US in July 2017 (DAY17). Trustworthiness estimates (N = 39) were provided by five software SMEs on the seven trustworthiness sub-dimensions, plus an overall estimate of trustworthiness, for six individual system functional components. The results are shown in Figure 5-29 together with comparison benchmarks for the range of single dimension trustworthiness estimates (4.83-6.01) provided from the earlier UK WITS MUMT Trial. The results show substantial variability in the ratings provided for the individual ratings dimensions and software components, indicative of sensitivity, discriminative and diagnostic power. UK COMPACT, for example, was rated high (6) on Reliability, Dependability, Predictability, and lower on Resilience (4), Safety (4) and Security (2).

Figure 5-30 compares the results of HAT CMM testing in the C2 of Autonomy DAY17 SE Trial and the UK MoD UAS LVC trial conducted in Cardigan Bay 2017, 18 – 22 September 2017 (CB17Air). Both trials used

three use cases derived from the Joint Warrior scenario described in Chapter 3 on Military Relevance. DAY17 used an advanced Multi-UxV control station, based on the AFRL IMPACT system, operated in turn by three Military SMEs from USAF, British Army and Australian Navy. CB17Air involved simulated Maritime Helicopter (HMA), Tactical UAS (Watchkeeper) and live-flight Small UAS, operated by UK Military SMEs from control stations, under JTAC Mission Command with a representative multi-tier Operational ISR and C2 capability. The results show differences in CMM maturity levels between the SE and LVC trials, reflecting differences in the operational and technical systems readiness under test, with evidence for progressive improvement in CMM in the LVC environment.

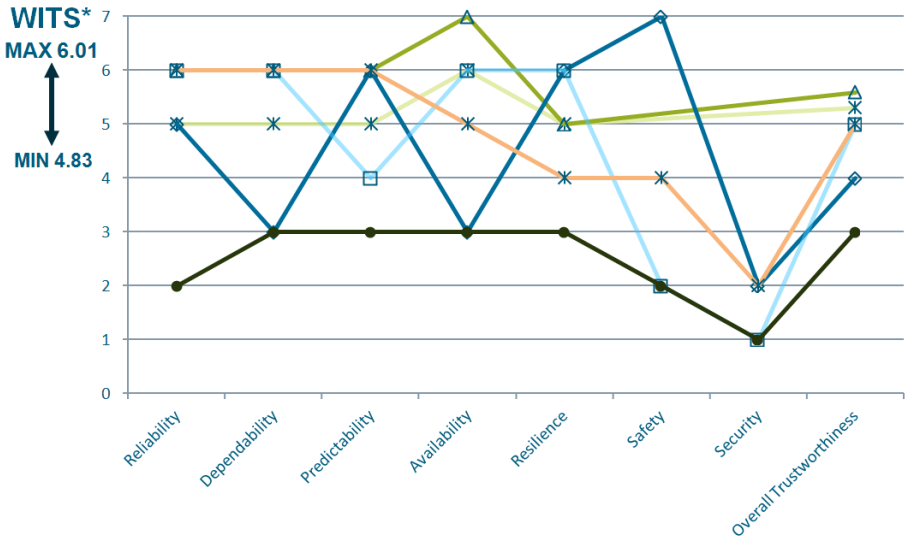


Figure 5-29: Multi-Dimensional Trustworthiness Ratings for Individual System Functional Components in DAY17 C2 Autonomy SE Trial.

5.6.12 Summary of Any NATO Communications/Collaborations/Interactions

	Planning/Design	Execution	Analysis
Communication	X		X
Coordination	X		
Collaboration			

5.6.13 NATO HAT Metrics Workshop

Under NATO TG HFM-247 HAT, a technical workshop on HAT metrics was held in Farnborough UK on 7 Nov 2016. The workshop was well attended by 11 NATO HAT researchers, with participation from UK, US, Sweden and Germany. The UK research on HAT metrics was fully briefed and discussed in depth. The meeting identified requirements for HAT framing cycles, internal/external performance parameters, veracity and rationality, with a "deep dive" into metrics for policy rationality, negotiation and working agreement patterns. It was agreed that good progress had been made on developing HAT metrics, but that further research was needed to develop understanding of the requirements for, and provide proof of the military benefits of, Human-Autonomy Teamwork vs. Human or Automation Teamwork.

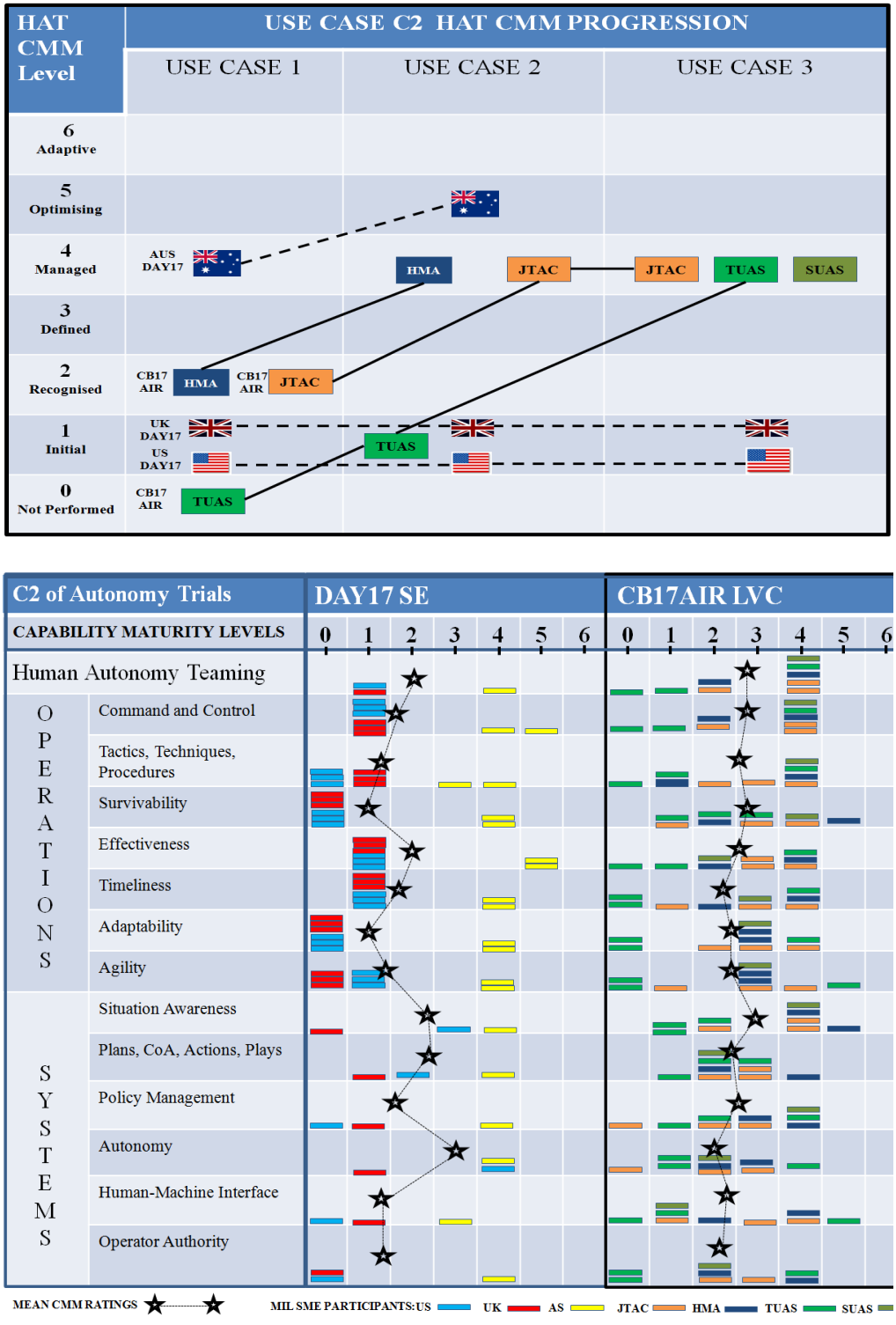


Figure 5-30: HAT CMM Results from DAY17 SE and CB17Air UAS LVC C2 of Autonomy Trials.

5.6.14 Summary of the TA Results

The UK Research Programme on Autonomy and Mission Systems, 2000 to present, has focused on the testing of autonomous systems concepts and mission enabling technologies in representative military scenarios and test environments. This TA report describes the key lessons learned on test and evaluation requirements of autonomous mission systems, including test methodologies and test design criteria and variables for SE and LVC testing. It includes the development of mission critical decision methodology involving the capture of taskwork and teamwork performance metrics and benchmarks (CAPTEAM). The results of recent UK research on Manned-Unmanned Teaming testing in SE and LVC environments is described, with management of variable collaborative adaptable autonomy using automated policy management and negotiation agreement technologies. This work has included the development of models and metrics for HAT, providing testing of HAT Trustworthiness and HAT Capability Maturity metrics, the results of which are described, providing confidence in the validity and reliability of the HAT models and metrics.

5.7 US-1: HUMAN-AUTONOMY TEAMING IN A FLIGHT-FOLLOWING TASK

5.7.1 HAT Approach Description

This section summarizes two papers, Refs. [109], and [110] that describe a study demonstrating and evaluating proposed tenets of Human-Autonomy Teaming (HAT) in an aviation context. In this study, HAT features were derived from three tenets and built into an automated recommender system on a ground station. These HAT tenets were:

- *Bi-Directional Communication*. Communications between humans and autonomous agents are necessary for establishing and maintaining a shared knowledge of task goals, exchanging information, and reporting errors (human- or autonomy-based) and status.
- *Automation Transparency*. The operator must understand the automation agent's intent and reasoning, and be able to elicit additional factors on which the agent has based a recommendation for a course of action. Operators must be able to see what the agent is doing and, ideally, predict what the agent will do next. Transparency requires operator knowledge of the general logic of how the agent works and accurate mental models of its functioning [111]. At the same time, the autonomous agent must understand (to some extent) the current goal, preferences, attitudes and states of human operators in the team. To be truly transparent, communication should use a shared language that matches the operator's mental model.
- *Operator Directed Interface*. Effective communication requires that the human operator can easily and accurately direct the automation, and override autonomous-system decisions, if necessary. Dynamic allocation of tasks based on operator direction and context also allows a more agile, flexible system and helps keep the operator in the loop.

This study focused primarily on interactions with one piece of automation, the Autonomous Constrained Flight Planner (ACFP). The ACFP is designed to support rapid diversion decisions for commercial pilots in off-nominal situations [112]. The ACFP compiles information from several sources such as ATIS broadcasts, METAR weather reports, GPS location and terrain, aircraft condition, and airport/runway characteristics. Evaluations are made for various factors (e.g., risk associated with the enroute, approach, and landing phases of flight, fuel usage, weather, terrain, distance, facilities). These evaluations are then aggregated to produce an overall score. Much effort has gone into enhancing this tool not only in capability but also in transparency [113], [114], [115]. In this study, participants used the ACFP at a ground station designed to aid dispatchers in a flight-following role to reroute aircraft in situations such as inclement weather, system failures and medical emergencies. Participants performed this task both with HAT features enabled and without, and provided feedback.

5.7.2 Method

5.7.2.1 Participants

Four dispatchers (median dispatch experience was 11 years) and two pilots (both active duty and each with over 10,000 hours flown as a line pilot) participated in this simulation.

5.7.2.2 Simulation Environment

Our simulation ground station is described elsewhere [116], [117], [118]. Both the ground station and the concept of operations have evolved through a series of development and test cycles (i.e., "spiral development"). Our current concept of operations [118] envisions a role for ground support in monitoring and assisting aircraft in an advanced flight-following mode, that requires increasingly sophisticated automation and enhanced collaboration between the operator and the automation. The following sections describe the components of the ground station focussing on the HAT features included for this simulation.

5.7.2.2.1 Aircraft Control List

The center of the station hosts an Aircraft Control List (ACL), the primary tool for managing multiple aircraft and switching the focus between aircraft (see Figure 5-31(A)). The ACL provides information crucial for situation awareness such as callsigns, departure and destination city pairs, estimated time of arrivals, flight plans, souls on board, and pilot details. This version of the ground station was designed to monitor, with the help of automation, a large number of aircraft (up to 30). Alerts were issued for failure to adhere to a clearance, failure to stay on path, environmental threats (weather on flight path or at the destination, and airport closures), system issues, and failure of the pilot to acknowledge a flight deck alert.

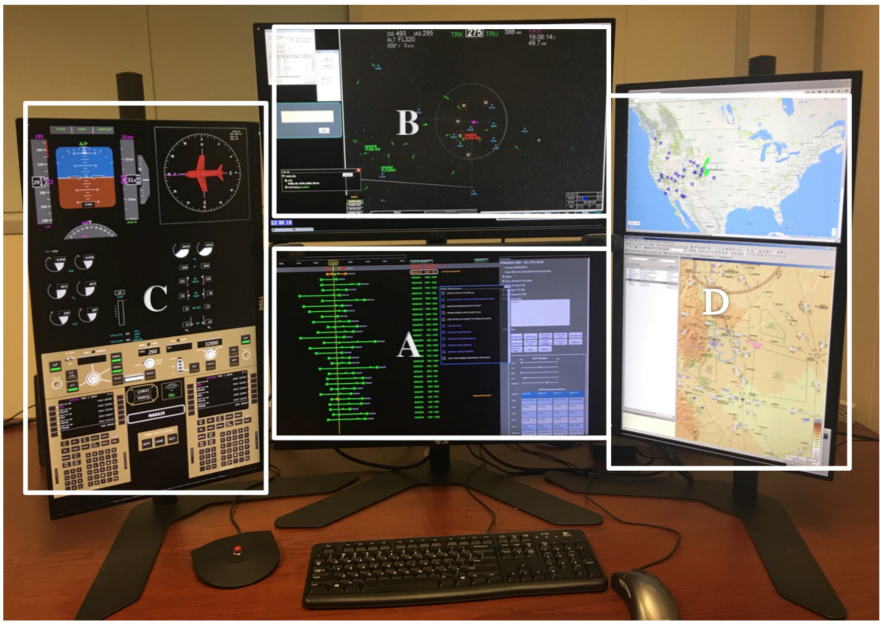


Figure 5-31: Simulation Ground Station. (A) Aircraft Control List (ACL), augmented with timeline, alerting information and HAT features. (B) Traffic Situation Display (TSD). (C) Flight controls and displays for the selected aircraft in read-only mode. (D) CONUS map and charts.

- *Operator Directed Interface*. We have adopted the playbook approach to set system goals and manage roles and responsibilities between the operator and the automation [119]. When the operator selects a play, the ACFP is triggered with preset weights and the corresponding checklist appears on the display identifying operator tasks in white and automation tasks in blue (see Figure 5-32).

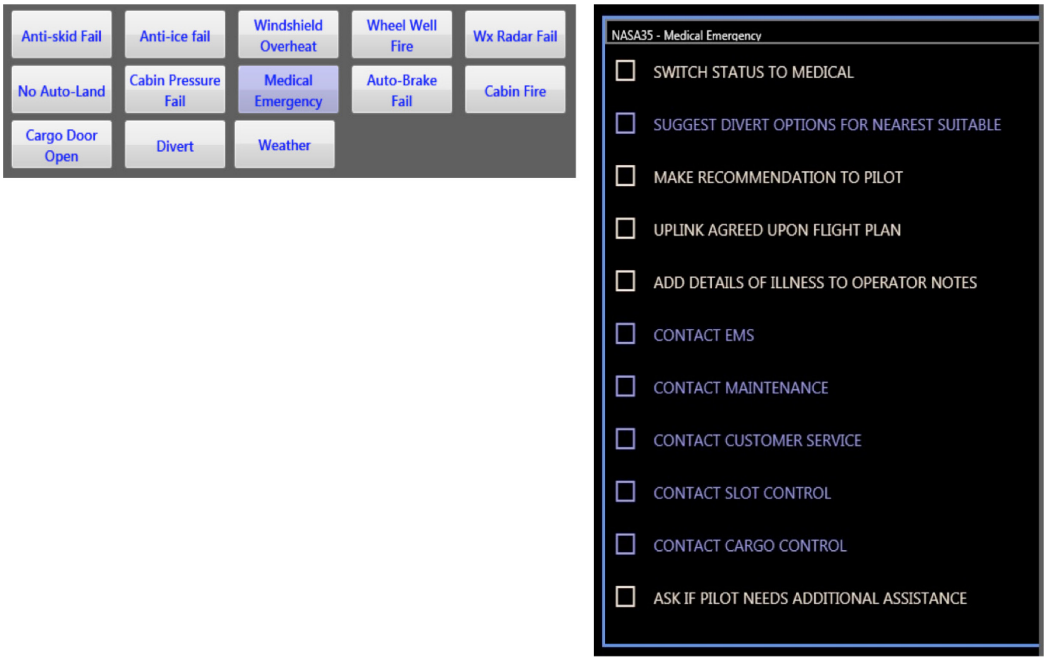


Figure 5-32: Playbook and Checklist.

Note: Operators could call plays for various events and in the HAT condition were provided a checklist of roles and responsibilities. This is an example of a Medical Emergency play.

- *Building in Transparency*. The ACFP has the capability of weighting the factors that go into its recommendations differently based on the situation. We increased transparency by explicitly showing these factors and weights when the ACFP is enabled (see Figure 5-33). Additionally, we translated the scores for the ACFP factors to more meaningful numbers and descriptors for the operator (e.g., presenting nautical miles (nm) instead of a distance score). In the example above, a Medical Emergency play was called which resulted in the distance to medical facilities (Medical row) and time to destination (ETA row) given more weight than other factors.

- *Building in Bi-Directional Communication*. We preset weights for each play and presented the weight settings (top of Figure 5-33). The operator can adjust the weights to better fit the situation and see how the recommendation is affected. Again, using the example in Figure 5-33, the operator could adjust the ACFP weight for estimated time of arrival if that was deemed a higher priority than quality of medical facilities.

5.7.2.2.2 Traffic Situation Display

The Traffic Situation Display (TSD) is a 3D map displaying company aircraft (see Figure 5-31B). Information such as flight plans, trajectories, weather, terrain, and airports can be displayed:

- *Building in Transparency*. The ACFP was augmented to display ATIS at the recommended divert airport as well as indicate which of a number of risk factors are present in any potential divert location (see Figure 5-34) [114], [115].
- *Building in Bi-Directional Communication.* Operators could also request such ratings for airports that are not recommended by the ACFP.

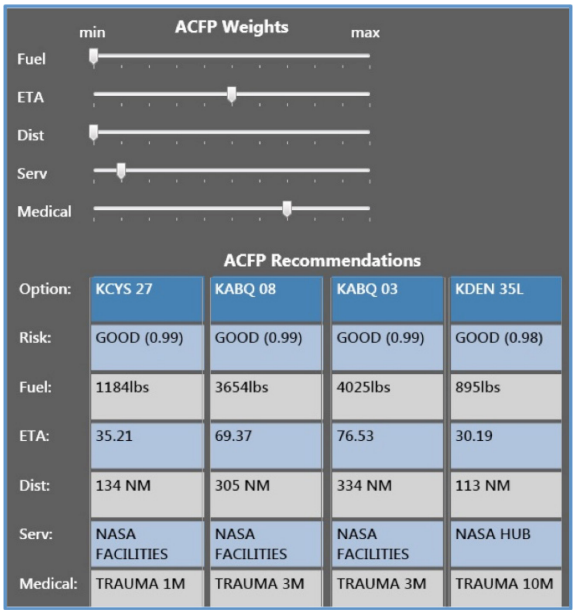


Figure 5-33: HAT Weights (Top) and ACFP Factors (Bottom).

Note: In the HAT condition, operators were provided ACFP factors (on bottom) and weights (on top) to increase transparency and bi-directional communication. This is an example from a Medical Emergency play.

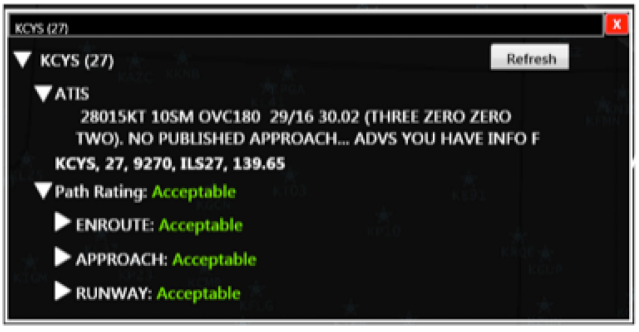


Figure 5-34: Traffic Situation Display Transparency Window.

Note: When using the ACFP, regardless of condition, a transparency window appeared on the TSD for the recommended airport. An ATIS report, runway information, path rating and reasoning statements were also included.

5.7.2.2.3 Additional Displays

The left side display containing aircraft flight controls and instrumentation for the selected aircraft (Figure 5-31C), and the right side display containing a CONUS map with an overlay of company aircraft and weather and airport charts are provided below the map (Figure 5-31D), were unchanged from previous simulations [118].

5.7.2.3 Experimental Design

The experimental design consisted of a single fixed factor, HAT, and a random factor, Participant. There were two levels of HAT: HAT (ground station with HAT features enabled) and No HAT (ground station without HAT features). Participants performed the flight-following task once in each condition with the order of trials counterbalanced across participants. We collected behavioral and subjective data.

One participant was tested per day. Each participant received approximately 3.5 hours of training before running two 50-minute experimental scenarios. Participants were provided with a concept of operation where automation and ground personnel provide "another set of eyes" monitoring aircraft. The role of ground in this flight-following task was to support aircraft in high workload and off-nominal situations. Our primary interest was in participant feedback of the HAT features.

The operators had 30 aircraft to flight-follow from take-off until landing. Shortly into the scenario, the operator began being notified of various events. An event started either with an alert on the ground station, elevating the aircraft priority and queuing the operator to contact the pilot, or with a radio call from the pilot. In either case, if it was determined that the aircraft needed to divert to a new destination, the operator would invoke the ACFP by selecting the appropriate play. In the HAT condition, once the play was selected, a checklist of procedures appeared indicating that the automation was responsible for a certain set of identified tasks. In the No HAT condition, operators had a paper checklist available for procedure items. In both conditions, the ACFP provided multiple recommendations in rank order and the transparency window was displayed on the TSD for the selected airport (see Figure 5-34). The ACFP would select the highest rated airport based on the event and related factors, though the operator could explore additional airports and view both the suggested route and transparency window. In the HAT condition, the ACFP factors and weights were displayed on the ACL providing additional transparency and allowing for manipulation of factor weights. The operator would discuss options with the pilot and, when there was consensus on the new airport, the operator would datalink the route to the pilot who would, according to the concept of operations, contact air traffic control for approval. Operators could then determine to what extent they needed to follow that aircraft.

5.7.3 Results

5.7.3.1 Workload

Workload ratings were obtained at regular intervals throughout the scenarios. One subject did not respond to workload queries throughout the simulation; therefore, a repeated measures ANOVA was performed on workload ratings for the remaining five participants with the factors HAT condition and time in scenario. Overall, workload ratings were low. While the workload ratings in the HAT condition ($M = 1.65$, $SEM = 0.93$) appeared lower overall than ratings in the No HAT condition ($M = 2.33$, $SEM = 1.24$), the difference was not significant ($p = .13$; see Figure 5-35). The interaction between HAT condition and time interval was significant, however, $F(5,11) = 3.42$; $p = 0.04$. For the HAT condition, workload ratings were generally lower, and decreased slightly with time in the scenario. Workload ratings for the No HAT condition were more variable and roughly constant throughout. When asked post-simulation which displays and automation was preferred to reduce workload necessary for the task, all participants selected the HAT condition.

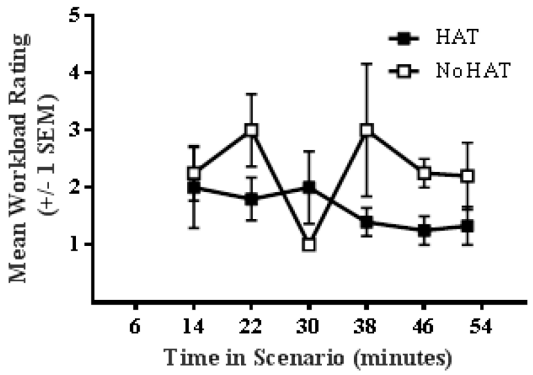


Figure 5-35: Workload Ratings for HAT and No HAT Conditions at Regular Intervals in the Scenarios.

5.7.3.2 Eye Gaze Durations

Eye gaze data was obtained from two cameras mounted on the ground station monitors. Data were collected and analyzed in both conditions only for events resulting in a flight plan change based on the ACFP. The duration of the event was the time between activation of a play and uplink of a flight plan. This event time was subsequently broken down by the amount of time spent gazing at each of the five displays (Flight Controls, TSD, ACL, CONUS map, and Charts) during the event, by examining the gaze direction relative to each camera.

Table 5-7 summarizes differences between conditions in terms of event and eye gaze durations. From this table, it can be seen that participants did not always uplink a flight plan change for each event. On average only three flight plan changes were made per scenario under each condition. However, in the HAT condition, the amount of time to select and uplink a flight change was significantly longer (40 s longer), compared with the No HAT condition. The increase in event times was due to participants gazing significantly longer at the ACFP (where the recommendations and weights were displayed) and the TSD (see Table 5-7) in the HAT condition. Some of the increased time must have been caused by slider movement; however, when restricting gaze times to events in which no slider movement occurred the difference between the mean gaze time for HAT was still higher (and marginally significant) compared with the No HAT condition. Very little time was spent gazing at the remaining displays in either condition.

Table 5-7: Summary of Flight Plan Changes in Response to Off-Nominal Events and Time Spent on Ground Station Displays for HAT and No HAT Conditions.

Summary Statistic	HAT	No HAT	p*
Mean (SEM) number flight plan change(s)	3.3 (0.8)	3.0 (0.6)	.78
Mean (SEM) time per flight plan change(s)	101.2 (19.4)	63.7 (14.9)	.026
Mean (SEM) gaze time on ACFP(s)	53.6 (9.5)	27.5 (3.5)	.009
Mean (SEM) gaze time on ACFP(s) – sliders not moved in HAT condition(s)	41.9 (8.7)	27.5 (3.5)	.08
Mean (SEM) gaze time on TSD(s)	38 (14.0)	20.7 (11.0)	.10
Mean (SEM) gaze time on other displays	11.9 (13.0)	9.05 (12.3)	.28

*probability of obtained difference based on repeated measures t test (*df* = 5)

5.7.3.3 Weight Adjustments

For the HAT condition, we counted the number of times the participant adjusted the weight factors prior to uploading a flight plan. As shown in Table 5-8, these weights were rarely adjusted, and these adjustments were restricted mostly to one off-nominal event.

Table 5-8: Number of Participants Who Adjusted Factor Weights by Event in the HAT Condition.

Event	N Participants	Factor(s) Adjusted
Fire in Lavatory	5	Distance
Airport Weather	2	Distance, ETA
Wheel Well Fire	1	ETA
Medical Emergency	1	Distance and ETA

5.7.3.4 Post-Scenario Comparisons

A post-simulation questionnaire was administered after both trials were completed. Participants were asked to rate their preferred displays and automation on a 1 = No HAT to 9 = HAT scale. Participants unanimously preferred the HAT displays. Specifically, HAT displays were preferred with regard to:

- Keeping up with operationally important issues (M = 8.67, SD = 0.52);
- Ensuring the necessary situation awareness for the task (M = 8.67, SD = 0.52);
- Integrating information from a variety of sources (M = 8.67, SD = 0.52); and
- Efficiency (M = 8.33, SD = 0.82).

Participants were in agreement that overall they preferred interacting with the automation in the HAT condition (M = 8.50, SD = 0.55).

HAT Features. Items specific to the HAT tenets were rated both post-scenario and post-simulation:

- *Bi-Directional Communication*. Participants agreed that the ACFP weights improved the automation's ability to handle unusual situations (M = 7.83, SD = 1.60) and were useful in making divert decisions (M = 8.33, SD = 0.82). Participants liked having the weights (M = 8.33, SD = 1.21) and one participant commented that, *"[the display] gave me the ability to see why, gave me control to change weights in variable(s)."*
- *Transparency*. Participants agreed that the ACFP table was helpful in making divert decisions (M = 7.67, SD = 1.51) and they liked having the table (M = 8.33, SD = 1.03). One participant commented that, "*This [table] is wonderful… You would not find a dispatcher who would just be comfortable with making a decision without knowing why*."
- *Operator Directed Interface with Plays.* Participants liked having the electronic checklist for each play (M = 8.67, SD = 0.52) and preferred the electronic to the paper checklist (M = 6.33, SD = 1.97). One participant claimed that, *"The electronic list was easier because it was right there on the screen and it eliminated a couple of the steps."* Another participant was hesitant to rely solely on the electronic checklist and explained that he/she, *"found it necessary to have both on hand."*

5.7.4 Summary of Any NATO Communications/Collaborations/Interactions

	Planning/Design	Execution	Analysis
Communication	X	X	X
Coordination	X		
Collaboration			

5.7.5 Future Research Needs and Plans in This Area

We examined subjective and behavioral indicators of HAT collaborations using a proof-of-concept demonstration of HAT tenets: bi-directional communication between the human and automation, transparency for automation, and an operator directed interface. Because this was primarily a demonstration, the low number of participants resulted in limited statistical power. Nevertheless, the data collected that suggest potential advantages and disadvantages of HAT.

Overall, participant feedback was positive, supporting our implementation of HAT features. Participants liked having a recommender system with factors and weights and expressed interest in having similar automation for real flights. They valued the integration of the displays, commenting that this level of integration is not currently available. Participants found the electronic checklist useful as were a number of the alerts.

Operator workload appears to be lower in the HAT condition and decreased with time in the scenario. Seeing that participants completed only one scenario with the HAT agent, this may point to the need for additional training. In the No HAT condition, workload was higher and roughly constant throughout.

Interestingly, while workload was rated lower, participants took more time to uplink flight plan changes in the HAT condition, even when no weighting adjustments were made. Typically, longer task times indicate higher workload. However, given that workload overall was very low, and that very few flight plan changes were made in each scenario, it is possible that the increases in event times were insufficient to change subjective workload. If this is the case, we speculate that in the HAT condition, providing an opportunity to alter the recommendations of the HAT agent led participants to consider the initial recommendations more carefully before either accepting or adjusting them. In the No HAT condition, if participants rejected recommendations of the ACFP, they would have to create a flight deviation with no automation assistance, and this may have led participants to accept recommendations with less prior evaluation. Of course, these speculations must be verified with further research.

These findings point out the difficulty in establishing behavioral and performance metrics for evaluating the effectiveness of HAT collaborations. On the one hand, longer event times might indicate higher workload and less efficient operations. Alternatively, longer event times might indicate more thorough processing, indicating that the HAT agent is improving operator and system performance. To understand the effect of HAT agents on operator performance and the quality of HAT collaboration, requires methods and measures be carefully developed and tested. We offer the following recommendations in this regard:

Evaluations of HAT must be performed at all levels of the system, and use a battery of assessment techniques. Evaluations must include system, autonomous agent, and operator performance as well as behavioral precursors to operator performance [120]. The latter measures include workload, situation awareness and trust in automation. HAT evaluations should also utilize subjective, behavioral and performance measures of effectiveness. Subjective measures are simplest; they can be administered at different times during a scenario

and capture the operator's perspective on the construct of interest. Note that, in our preliminary evaluation of the HAT agent for Rescued Crew Operations (RCO), weight adjustments were made primarily by only one of our six participants. Validated subjective measures of HAT effectiveness are currently unavailable; however, validated subjective measures of human-human collaborations do exist [121], and they represent a reasonable starting point in this regard.

Finally, performance measures of HAT effectiveness will necessitate carefully designed tasks and scenarios that are sensitive to differences brought about by a HAT agent.

We continue to work on the implementation of our HAT tenets. In particular, in our current implementation, plays were flat, including only simple checklists. We are working towards making these more flexible with varying levels of automation, branch points, and opportunities for bi-directional communication. Our goal is to develop a framework for HAT, consisting of tenets and guidelines for implementing them. We eventually hope to create software libraries that make this implementation easier.

5.7.6 Acknowledgements

We would like to acknowledge NASA's Safe and Autonomous Systems Operations Project, which funded this research.

5.8 US-2: INTELLIGENT MULTI-UNMANNED VEHICLE PLANNER WITH ADAPTIVE COLLABORATIVE CONTROL TECHNOLOGIES (IMPACT)

5.8.1 HAT Design Pattern Description

Using the HAT pattern taxonomy described in this report, IMPACT can be represented according to Figure 5-36.

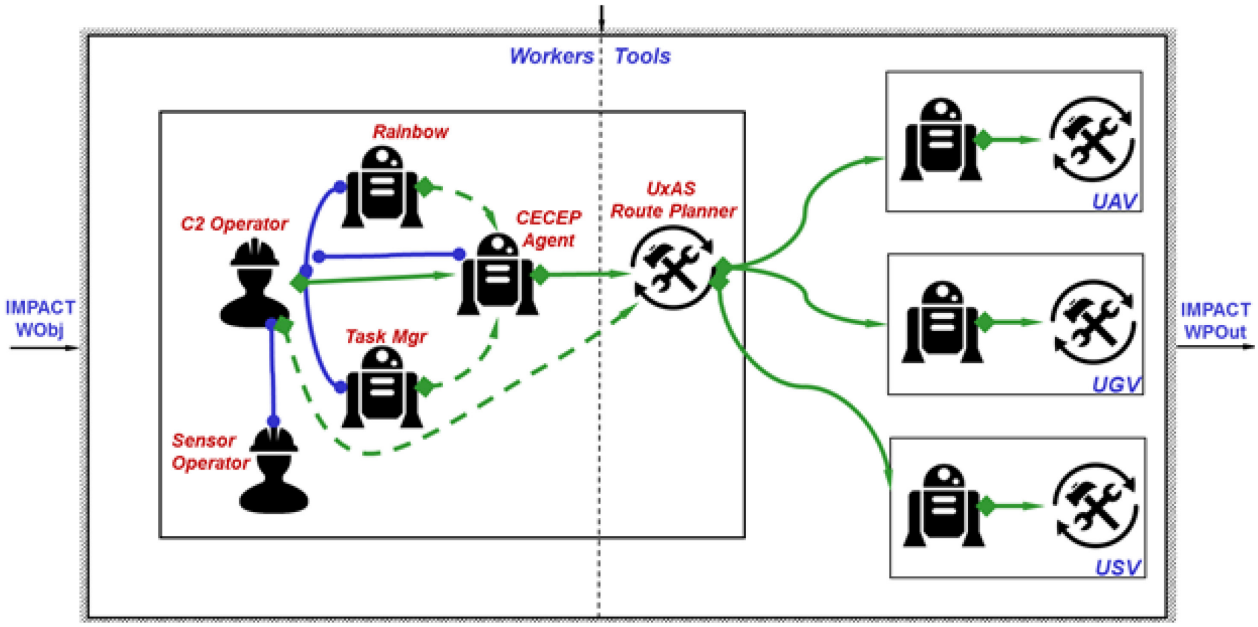


Figure 5-36: IMPACT Representation as a Layer 1 Pattern.

A work objective enters the system, often a tasking through a communications system such as chat messaging. In response, the Command and Control (C2) operator calls a play which results in the Cognitively Enhanced Complex Event Processor CECEP agent recommending a solution consisting of selected vehicles and the optimal routing provided by Unmanned Systems Autonomy Services (UxAS). The C2 operator can alternative choose to bypass the CECEP agent and personally select assets if the operator is aware of information that the agent is not. The CECEP agent assesses many different solution alternatives and recommends one or more courses of action. The Rainbow Autonomics agent monitors the executing plan and alerts if certain performance thresholds are breached. A task manager agent can also autonomously monitor, identify and ingest new tasking's for allocation to the C2 operator or CECEP agent for execution based upon operator performance and/or workload models. Agents can exist within each platform to perform local reasoning.

5.8.2 Detailed Description of TA

Agility in tactical decision making and mission management is a key attribute for enabling teams of heterogeneous Unmanned Vehicles (UxV) to successfully manage the "fog of war" with its inherently complex, ambiguous, and time-challenging conditions. This agility requires effective operator-autonomy teaming including the achievement of trusted collaboration and the flexible, high-level tasking required for team task sharing and decision superiority. A tri-service team has conducted research focused on instantiating an "Intelligent Multi-UxV Planner with Adaptive Collaborative/Control Technologies" (IMPACT) by combining flexible play calling for task delegation, bi-directional human-autonomy interaction, advanced cooperative control algorithms, intelligent agent reasoning, and autonomic technologies to enable effective single operator Command and Control (C2) of cooperative multi-UxV missions (Figure 5-37). An IMPACT operator, with intelligent assistance, was able to task and manage a total of 12 UxV (four air, four ground, and four sea surface vehicles) in response to several unexpected events that arose during an ongoing base perimeter defence mission.

Figure 5-37: IMPACT Control Station Prototype.

This TA focused on the central aspects of IMPACT: operator-autonomy interface design, intelligent agent architecture, UxAV routing algorithms, testbed framework and distributed architecture, autonomics and task management, and human-in-the-loop prototype evaluation.

5.8.2.1 Interfaces for Operator-Autonomy Teaming

IMPACT's displays and controls (Figure 5-38) feature video game inspired pictorial icons that present information in a concise, integrated manner to facilitate retrieval of the states/goals/progress for multiple systems and support direct perception and manipulation principles. Multimodal controls (speech, touch, and mouse) augment a "playbook" delegation architecture and enable seamless transition between control states (from manual to fully autonomous). With this adaptable automation scheme, the operator retains authority and decision-making responsibilities that help avoid "automation surprises". By supporting a range of interactions, flexible operator-autonomy teamwork enables agility while responding to a dynamic mission environment. At one extreme, the operator can manually control UxV movement or build plays from the ground up, specifying detailed parameters. At the other extreme, the operator can quickly task one or more UxVs by only specifying play type and location with an intelligent agent determining all other parameters. For example, when an IMPACT operator calls a play to achieve air surveillance on a building, the intelligent agent recommends a UxV to use (based on Estimated Time Enroute (ETE), fuel use, environmental conditions, etc.), a cooperative control algorithm provides the shortest route to get to the building (taking into account no-fly zones, etc.), and an autonomics framework monitors the play's ongoing status (e.g., alerting if the UxV won't arrive at the building on time). IMPACT's play calling interfaces also facilitate operator-agent communication on mission details to optimize play parameters (e.g., target size and current visibility) as well as supporting operator/autonomy shared awareness (e.g., illustrated by a display showing the trade-offs associated with multiple agent-generated courses of actions across mission parameters). Play progress is depicted in a matrix display reflecting autonomics monitoring and a tabular interface aids play management (e.g., allocation of assets across plays). Additional detail on all the play-related interfaces is available [122].

Figure 5-38: IMPACT Operator-Autonomy Interfaces.

5.8.2.2 Intelligent Agent Framework for Course of Action Generation

UxV allocation, tasking, and management capabilities were provided in IMPACT via an intelligent agent that was developed using the Cognitively Enhanced Complex Event Processing (CECEP) framework. This capability allows for an operator to communicate high-level details about a desired play call such as location or optimization criteria (e.g., time, fuel). In response, the agent provides the operator with a ranked set of Courses of Action (CoAs) that were formulated based on low-level task details. This approach was expected to alleviate workload burden of the operator by having the autonomy focus on the low-level details while allowing the operator to tend to higher-level mission objections.

CECEP is a complex event processing framework with extended procedural and domain knowledge aspects. Agents that use procedural knowledge were developed using a discrete finite state machine called behavior models that include states and transitions between states that are guarded by patterns. A pattern language called Esper was used to match complex patterns of operator and UxV behaviors to transition states at runtime. Behavior models were used to produce behaviors (e.g., feedback for the operator or UxV play execution). Agents that use domain knowledge were developed using Cognitive Domain Ontologies (CDOs). A CDO is a rooted tree structure with features that are connected via relations. CDOs can be processed using the AI process of constraint satisfaction to produce configurations, possible worlds, or CoAs. CDOs were developed to capture the domain for UxV play calling and produce CoAs for play-vehicle(s) assignment.

The IMPACT agent serves as a decision aid to a multi-UxV operator. The agent is integrated with a UxV route planner (UxAS), Fusion framework, plan monitoring service (Rainbow), and UxV simulator (AMASE). The operator's play calls are used as a starting point for generating CoAs, with the play type (e.g., air point inspect), presets (e.g., cloudy, windy), and optimization criteria (e.g., time, fuel) forming the basis of domain knowledge used to constrain and rank possible CoAs. Figure 5-39 describes IMPACT's play calling process.

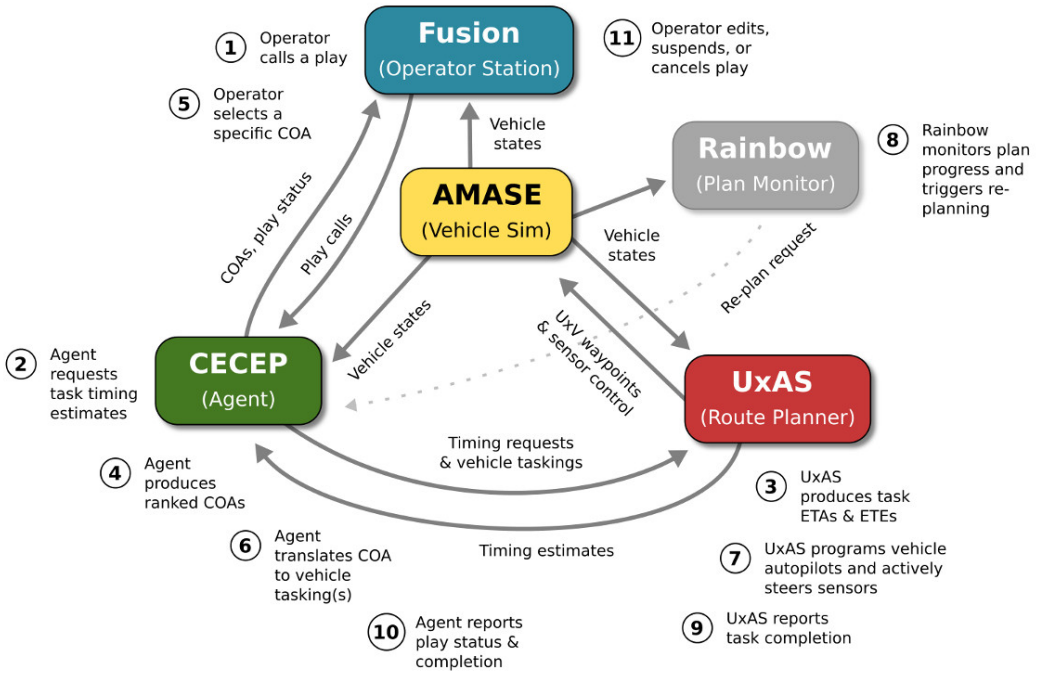


Figure 5-39: Play Calling Process in IMPACT. See list below for further information on each numbered item in the figure.

Here is further information on each numbered item referred to in Figure 5-39:

1) A play call commonly originates from the operator. However, the agent is capable of monitoring the vehicle locations and recommending opportunistic or serendipitous plays, such as inspecting the fuel storage by a vehicle already in the area.
2) The agent transforms play calls into lower-level tasks for the UxAS route planner and requests task assignment utility from it (knowledge about task timings, fuel usage, and communication issues from the route planner).
3) The agent asserts the acquired knowledge to the play calling CDO domain representation.
4) The agent applies all constraints corresponding to the operator provided play details. The CDO is processed to produce all constraint compliant CoAs. The agent uses an objective function to rank CoAs and identify the Pareto optimal CoA in a list and on a map presented to the operator. A visual is also produced that allows the operator to compare CoAs by solution utility. If no constraint compliant solutions exist the agent informs the operator.
5) The agent waits for operator acceptance, edit, or cancelation of a CoA. Upon acceptance; the agent produces the vehicle action command to the UxAS to execute the CoA.
6) The UxAS programs vehicle autopilots and actively steers sensors and sends behaviors to the simulator.
7) The plan monitoring service monitors the active play and displays feedback to the operator if a constraint is violated (e.g., a UxV enters a restricted operating zone).
8) The agent waits for a task complete message from the UxAS.
9) The agent reports plan status to the operator to improve operator situation awareness.
10) The agent waits for operator to edit, suspend, or cancel the active play.

5.8.2.3 UxAS Routing Algorithms

Current ground control stations for unmanned vehicles provide relatively low levels of autonomy, e.g., automatically commanding an assigned vehicle to follow a sequence of waypoints generated by a human operator. To increase the level of autonomy of UxVs, the Unmanned Systems Autonomy Services (UxAS) software architecture provides flexible and adaptive automated path planning, sensor steering, and inter-vehicle coordination for unmanned air, ground, and surface vehicles. UxAS consists of a collection of modular services that interact via a common message passing architecture, which makes it easy to add new services. Currently, UxAS provides approximately 50 services that automate vehicle route planning and sensor steering, coordinate behavior between cooperating vehicles, connect with external software and hardware devices, validate mission requests, log and diagram message traffic, and optimize play ordering with respect to total time required or distance travelled.

More specifically, UxAS provides services that automatically generate waypoints and sensor steering commands for search and surveillance plays over points, lines, and areas, with many tuneable parameters. UxAS also provides services that generate routes between plays based on vehicle type, e.g., so that ground vehicles stay constrained to roads. In addition to services that plan static routes, UxAS provides services that can update routes and sensor steering commands adaptively online, including for teams of cooperating vehicles. In general, UxAS services plan vehicle routes that account for factors such as regulatory “no-fly zones,” physical boundaries such as roads and terrain, and kinematic vehicle constraints such as minimum turn radius. In IMPACT, the intelligent

agent queries UxAS about the cost of routes needed to perform a play and uses the information to help determine which vehicles to assign. The appropriate UxAS services then carry out execution of the play by implementing routing, sensor steering, inter-vehicle coordination, and online adaptation during play execution.

5.8.2.4 Autonomics and Task Management

Autonomic approaches manage complex systems such that they exhibit self-adaptation in response to system demands or degradation of performance. One such autonomics approach is the Rainbow Autonomics Framework, developed at Carnegie Mellon University (CMU). Rainbow can manage systems that can be described as networks within the network model held within the framework. In IMPACT, the control team made up of humans and autonomous assistants was modelled as a network of servers that work tasks from task queues. Inherent in the autonomics framework are probes, gauges, and strategies. Probes read data from the underlying system, gauges aggregate that data, and strategies manipulate the network to improve performance.

Task manager capability includes the automatic generation of tasks from event information. By reading event information (e.g., from chat messages), the task manager generates tasks and parses out necessary information to aid in the completion of the task. Task-guided Human-Machine Interfaces (HMI) help users complete tasks (e.g., calling plays) by making calls to appropriate tools within IMPACT and prepopulating with data from the events. Tasks can be directed towards autonomous assistants that are capable of completing some tasks, and queue management tools are provided to the operator.

5.8.2.5 Fusion and the Distributed Architecture Services

Fusion is a software framework that enables natural human interaction with flexible and adaptable automation [123]. A distributed service-oriented architecture is employed that is composed of multiple disparate systems, unified representationally through negotiated communications protocols and physically through a common communications hub. The decentralization of the architecture enables logging, monitoring, and substitution of components with minimal effect on other components. Thus, several different systems can indirectly interact with one another through a publish/subscribe hub to provide a greater service to the user. All connected pieces communicate through a common messaging protocol to send and receive information. Connected services developed for IMPACT include intelligent agent reasoning among disparate domain knowledge sources, autonomics monitoring services, intelligent aids to the operator, cooperative planners, and advanced simulation via instrumented, goal-oriented operator interfaces. The distributed architecture along with an extensible software framework enables the system to be expanded for other human-automation research.

The Fusion architecture includes the core (customizable) aspects that are common across applications as well as features that support the IMPACT project. The Fusion test bed also displays the scenario environment, presents mission events that prompt UxV management tasks, provides a workspace for the operator to team with autonomy to complete tasks, and records task performance measures. Other IMPACT specific components provide interfaces for calling and modifying plays, viewing agent-generated candidate CoAs, and presenting the results of an autonomics service monitoring play progress.

5.8.2.6 Operator-in-the-Loop Evaluation of Operator-Autonomy Teamwork

In the first year of this project, an initial assessment took place to gauge the perceived utility of various technologies under development [124]. At the end of the project, a more comprehensive, high-fidelity human-in-the-loop simulation evaluation of IMPACT was conducted. In this evaluation, the current IMPACT prototype was compared to a baseline system that represented the current state-of-the-art for UxV control at the beginning of the effort. The

baseline system included a subset of IMPACT's capabilities such as the route planner and an associated interface. However, the baseline system lacked agent assistance, plan monitoring, and speech control. The experimental design was a 2 (Baseline, IMPACT) x 2 (low, high mission complexity) within-participant design with the order of conditions blocked by system (half of the participants used IMPACT first, the other half with Baseline) and counterbalanced across task complexity. Mission complexity was manipulated by varying the number and timing of tasks. Each of eight participants (all familiar with base defence and/or unmanned vehicle operations) performed four 60-minute base defence missions after a full day of training. Participants completed a variety of defence mission related tasks involving twelve simulated UxV. Participants' task performance was better on multiple mission performance metrics with the IMPACT system in comparison to the baseline system. Participants were also able to execute plays using significantly fewer control inputs with IMPACT as compared to baseline. The overall usability of each system was assessed using the System Usability Scale (SUS) [125]. Participants rated IMPACT higher than baseline on all ten SUS items and the overall SUS score was significantly higher with IMPACT than with baseline. Participants also subjectively rated IMPACT significantly better than baseline in terms of its perceived value to future UxV operations as well as its ability to aid workload. In fact, every participant gave IMPACT the highest possible score for potential value, and all but one participant gave IMPACT the highest possible score for its ability to aid workload. Table 5-9 summarizes some of the results from this evaluation.

Table 5-9: Evaluation Summary (IMPACT vs. Baseline).

Measure	Result	
Objective Measures	**IMPACT > Baseline**	**High Complexity < Low Complexity**
Rams Completed Correctly	*	**
Normal Base Defense Outcome Measure		
Normal Base Defense Process Measure	*	**
Intruder Events Outcome Measure		**
Intruder Events Process Measures	**	**
Response to System Failures / Environmental Events		**
Commander Query Accuracy		**
Commander Query Response Time		
Time to Call Plays		
Number of Clicks to Call Plays	**	

* significant at .05
** significant at .01

5.8.3 Summary of NATO Communications/Collaborations/Interactions

	Planning/Design	Execution	Analysis
Communication	X	X	X
Coordination			
Collaboration			

5.8.4 Conclusion, Future Research Needs and Plans

The IMPACT project produced significant knowledge in a number of areas important to autonomy-related capabilities. Not only did the project spur advancements in component technology development, model development, and general design understanding/guidance, but much was learned from the formal integration of key autonomy-related technologies into a single multi-UxV control station application. IMPACT also produced a robust "virtual lab" for continued human-autonomy teaming research. A three-station system (C2, Sensor Operator (SO), and Test Operator Console (TOC)) is available for organic wide-spectrum Human-Autonomy Teaming (HAT) evaluations with sites currently at the Air Force Research Lab, the Space and Naval Warfare Systems Command, and the Army Research Lab. A new vision for future human-autonomy systems was successfully conveyed to DoD senior leadership via many interactive demonstrations of the IMPACT system. This vision clearly illustrates that the human will continue to have a prominent role in interacting with increasingly autonomous technology, dynamically flexing between supervisor, teammate, or manual controller as conditions dictate. Finally, IMPACT technologies have extended/transitioned in a myriad of ways. Other projects have leveraged IMPACT technology to advance their aims while new DoD projects and several industry contractors now utilize IMPACT in autonomy technology development efforts. Additionally, IMPACT has become the core C2 autonomy piece within an international Autonomy Strategic Challenge project which is a three-year, five-nation effort to integrate and assess promising allied autonomy capability in mixed live/virtual multi-UxV littoral environments.

The IMPACT project has enabled a deeper exploration into the critical issues that influence flexible and effective human-autonomy collaboration. Although the IMPACT evaluation demonstrated military utility in several aspects related to operator-autonomy teaming, several deficiencies and gaps in understanding were also identified and improvements are underway. These include research related to novel methods for enabling bi-directional communication and management of temporal constraints, more naturalistic dialogue and sketch interactions, and consideration of information degradation and uncertainty in decision-making tasks. Additionally, research is investigating the effects of a decentralized re-planning capability, real-time operator functional state assessment, and alternative team structures on overall human-autonomy teaming. Finally, additional technologies such as policy management and a narrative explanatory capability are being integrated with IMPACT capabilities for an international live-virtual military demonstration of human-autonomy teaming. The results of these follow-on efforts will provide a much richer understanding of this area.

5.8.5 Acknowledgements

This work resulted from a successful collaboration between the US Air Force Research Lab, the Army Research Laboratory, and Navy SPAWAR under the sponsorship of the Assistant Secretary of Defence for Research and Engineering (ASD/R&E). Dr Michael Barnes, Dr Jessica Chen and Dr Doug Lange from HFM-247 were teammates on the IMPACT project, and their research contributions to IMPACT appear as separate TAs for this report.

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[3] See Section 5.11 for references cited in this section.

5.9 US-3: AGENT TRANSPARENCY

5.9.1 HAT Design Pattern Description

Effective collaboration between humans and agents depends on humans maintaining an appropriate understanding of and calibrated trust in the judgement of their agent counterparts. As autonomous systems become more intelligent and more capable of complex decision making [126], [127], it becomes increasingly difficult for humans to understand the reasoning process behind the system's output. However, such understanding is crucial for both parties to collaborate effectively, particularly in dynamic environments [128]. To address these issues, the *Situation Awareness-Based Agent Transparency* (SAT) model (Figure 5-40) was developed to support human situation awareness in human-agent teams [129], [130].

Situation Awareness-based Agent Transparency

Level 1: Goal

Agent's current status/actions/plans

- Purpose: Desire (Goal selection)
- Process: Intentions (Planning/Execution); Progress
- Performance
- Perception (Environment/Teammates)

Level 2: Reasoning

Agent's reasoning process

- Reasoning process (Belief/Purpose)
- Motivations
    - Environmental & other constraints/affordances

Level 3: Projections

Agent's projections/predictions; uncertainty

- Projection of future outcomes
- Uncertainty and potential limitations; Likelihood of success/failure
- History of Performance

Figure 5-40: Situation Awareness-Based Agent Transparency (SAT) Model.

At the first SAT level (SAT 1), the agent provides the operator with the basic information about the agent's current state and goals, intentions, and plans. This level of information assists the human's *perception* of the agent's current actions and plans. At the second level (SAT 2), the agent reveals its reasoning process as well as the constraints/affordances that the agent considers when planning its actions. In this way, SAT 2 supports the human's *comprehension* of the agent's current behaviors. At the third SAT level (SAT 3), the agent provides the

operator with information regarding its projection of future states, predicted consequences, likelihood of success/failure, and any uncertainty associated with the aforementioned projections. Thus, SAT 3 information assists with the human's *projection* of future outcomes. SAT 3 also encompasses transparency with regard to uncertainty, given that projection is predicated on many factors whose outcomes may not be precisely known [129], [131], [132], [133], [134]. Prior research has shown the positive effects of agents conveying uncertainty on joint human-agent team performance effectiveness and operator perceptions of agent trustworthiness [133], [135], [136].

This Technical Activity is part of the IMPACT program (see Section 5.8: US-2: IMPACT), supported by US Department of Defense's Autonomy Research Pilot Initiative [137]. The objective of IMPACT is to investigate issues associated with flexible play calling, global cooperative control and local adaptive/reactive capability, and bi-directional human-autonomy interaction in military mission contexts. In support of IMPACT's objective to explore human-agent teaming, a series of laboratory studies with a simulated agent that could be rapidly reconfigured (i.e., to convey different levels of transparency based on the SAT model) were undertaken with college students as participants. Specifically, the experimental design manipulations tested the impact of information transparency type and level on the participants' decision-making performance. The agent played the role of 'planner,' generating and suggesting vehicle and route plans for the human; while the human (the experimental participant) acted as 'decider,' reviewing those plans and choosing which are implemented [138]. Transparency of the agent's communication was manipulated in order to test its effect on the operator's decision-making performance. Our basic paradigm was adapted in a simplified form and coordinated with our IMPACT partners at the Air Force Research Laboratory [139], [140].

In the first study (Figure 5-41), completed by Mercado et al. [133] three levels of transparency were implemented according to the SAT model reviewed in Figure 5-40: SAT 1 (basic plan information), SAT 1+2 (added reasoning information), and SAT 1+2+3 (added projection information, including uncertainty). Results indicated that operator task performance was highest and trust best calibrated (complying with the agent's recommendations when it was correct and rejecting the recommendations when it was incorrect [141] when the highest level of transparency (SAT 1+2+3) was implemented. Additionally, this occurred without a detriment to response time or subjective workload. Finally, operators' subjective trust in the agent's ability to suggest and make decisions also increased with increased levels of agent transparency.

A replication of this study by Stowers et al. [142] involving slight changes to the interface (Figure 5-43) examined three similar conditions, while delineating uncertainty from other projection information. The conditions implemented were SAT 1+2 (reasoning), SAT 1+2+3 (added projection), and SAT 1+2+3+U (added uncertainty). Results indicated that operator performance was once again highest when the highest level of transparency (SAT 1+2+3+U) was implemented. Additionally, this occurred without a detriment to workload. However, in this study, response time significantly increased with increased transparency, suggesting that operators were spending a longer time reading and processing information portrayed in the higher transparency conditions. Finally, operators' subjective, state-based trust in the agent's ability to analyze information increased when higher levels of transparency information were displayed.

These studies collectively suggest that transparency on the part of the agent benefits the human's decision making and thus the overall human-agent team performance. As in a typical human-human team, this communication of relevant information can facilitate processing and decision making by aiding in the creation of a shared mental model between team members. What remains to be seen is how similar information on the part of the human (i.e., bi-directional transparency) can further facilitate the human-agent team performance.

Figure 5-41: Interface Used to Display Transparency for Study by Mercado and Colleagues (2016). Transparency information is communicated through the use of text, vehicle characteristics on the map, and a pie chart.

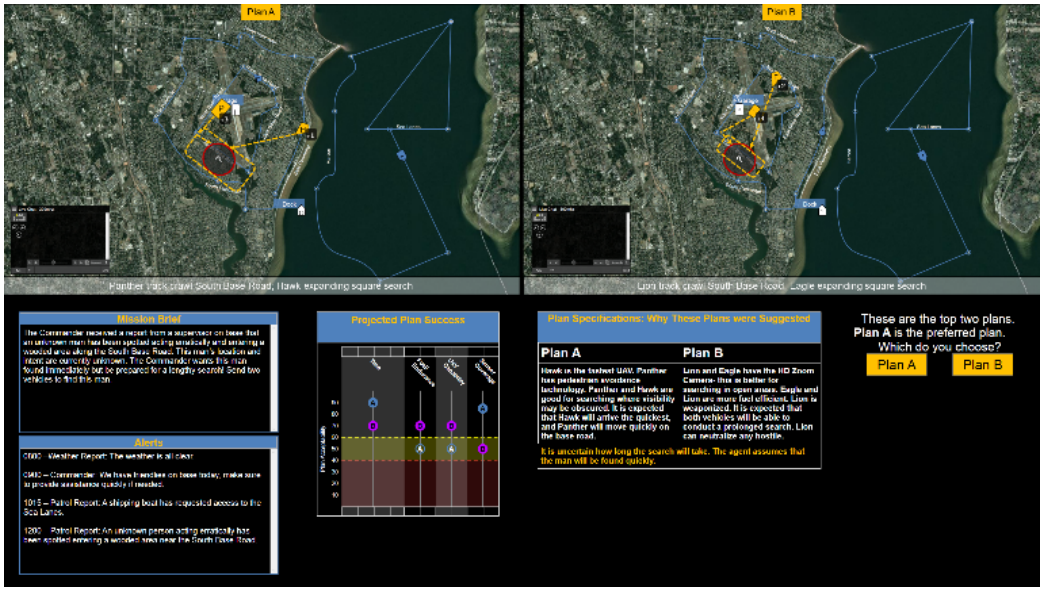

Figure 5-42: Interface Used to Display Transparency for Study by Stowers and Colleagues (2017).

Note: The interface was altered to pull transparency information to a separate area below the map, with text and a sliding bar scale representing the majority of transparency information offered. Vehicle characteristics on the map were also manipulated to correlate with such information.

5.9.2 Summary of Any NATO Communications/Collaborations/Interactions

	Planning/Design	Execution	Analysis
Communication	X	X	X
Coordination	X	X	
Collaboration	X		

5.9.3 Future Research Needs and Plans in This Area

Results from these studies completed as part of the IMPACT program yielded several insights to the utility of transparency, as well as best practices for implementing information transparency as part of an intelligent agent's interface. Primarily, it was found that agent transparency, as operationalized and implemented according to Chen et al.'s SAT model, is useful for improving performance in complex decision making such as that done in multi-UxV management tasks. Additionally, this performance is increased without a cost to workload. However, it should be noted that response time does increase for a few seconds, which may or may not create an issue depending on the mission environments. Overall, increased levels of transparency led to partially increased trust (in specific capabilities of the intelligent agent), while the effects of uncertainty information on operator trust are not always consistent.

Additional research is needed which explores human-agent teaming in a more bi-directional manner. Future studies will examine human-agent teaming with bi-directional communications to evaluate the utility of SAT-based interfaces in a dynamic manner [129]. This can be used to inform the design of field research being done with finalized intelligent agents that are capable of behaving independently. Additional efforts will also focus on developing a repository of user interface design elements (e.g., visualizations) to support SAT-based interfaces. Finally, ARL intends to continue their collaboration with IMPACT partners utilizing the IMPACT testbed.

5.9.4 Acknowledgements

We would like to thank our Air Force partners who helped us coordinate our efforts with the larger IMPACT program, especially Mark Draper, Gloria Calhoun, Kyle Beyhmer, Scott Douglass and Allen Rowe. We also acknowledge the essential contributions of the transparency research team: Daniel Barber, Kim Stowers, Nicholas Kasdaglis, Ryan Wohleber, Michael Rupp and Shan Lakhmani.

5.10 US-4: TASK MANAGEMENT AND PLAN MONITORING

5.10.1 Capability Description

5.10.1.1 Task Management

With the onset of a high volume of tasks, tasking can easily become overwhelming and disorganized, leading the operator to become less effective and focused in completing assigned tasks. To address these issues, as part of the Intelligent Multi-UxV Planner with Adaptive Collaborative/Control Technologies (IMPACT), a management system capable of determining user tasks, dividing tasks into a hierarchy, presenting tasks to the user, and providing a mechanism to execute an action for each task was developed (Figure 5-43).

Figure 5-43: Basic Task Manager Display. The figure shows a top-level task queue and expanded event information.

The tasks associated with this effort are tasks associated for execution by the human and not autonomous vehicles for which the tasking is applied. Autonomous systems or agents can support the human within the management of the tasks in terms determining and sorting the tasks. In cases of high workload an autonomous assistant can off load tasks, based on some workload agreement as to when and how this would occur, and perform the functions of that task.

When a task is defined, it is either assigned to a human supervisor or an autonomous agent assisting the supervisor. In order to complete the task, the assignee must choose from one or more methods. The method may consist of one or more subtasks. This structure repeats recursively until no further subtasks are required to complete the task. The Task Manager utilizes this model when generating tasks. Each task may be broken up into one or more subtasks, while subtasks may be broken down into even more subtasks.

Determining an instance in which a task must be created requires the Task Manager to observe the tactical situation and monitor communications. Tasks can be generated in a variety of ways. For instance, a query can be sent to an operator regarding an asset or whether a UAV can fly into a restricted area. Every event is forwarded through a data hub. By parsing chat and notification messages that pass through the hub, it is possible to ascertain the required information needed to generate tasks.

Task Manager can also be an entry point into introducing new concepts in HAT. We developed autonomous search and detection algorithms with the intention of having a human-in-the-loop interaction to enhance the algorithm's effectiveness. A scenario was developed where the algorithms were placed into an object detection operation. The idea being that one of the search algorithms would act as an autonomous agent sweeping an area for the target. An operator would be given the ability to interact with the agent, providing information regarding possible locations of the object and to increase or decrease the probability of a target's location at a given coordinate. Play calling from the Task Manager is shown in Figure 5-44.

The latest innovations currently being incorporated into the Task Manager involve helping the operator balance workload by tasking an autonomous assistant with extraneous tasks. The autonomous assistant provides the following services:

- Receiving tasking in order to balance the load of the operator;
- Executing the allocated tasking; and
- Alleviating operator tasking on lower priority or repetitive tasks.

In the future, these responsibilities will expand to include:

- Providing the operator feedback on task statuses or reminders for high priority tasking;
- Providing suggestions or data for decision points of crucial operator tasks; and
- Adjusting load balancing of tasks to fine tune load balance for the operator.

Figure 5-44: Play Calling from Task Manager. Tasks that require play calling lead directly into a play calling interface to assist operators with the task.

The autonomous assistant is designed to be tasked in two ways. First, the operator can manually assign tasks to the autonomous assistant by simply clicking a button. Tasks can also be reassigned to the operator by selecting the task from the Autonomous Assistant's task list. Second, the Autonomous Assistant may also be tasked via a simple load balancing algorithm. When the operator begins to be over tasked, lower priority tasks (such as queries) can be assigned to the Autonomous Assistant. When the Autonomous Assistant receives a task, it immediately executes the task in its queue.

5.10.1.2 Plan Monitoring

With a single operator overseeing teams of heterogeneous unmanned vehicle platforms performing multiple concurrent missions comes increased complexity that is difficult to monitor. A motivating factor for the live monitoring of mission plan progress and anomalies is increased operator SA and reduction of information overload. Measuring holistic plan health along with vehicle telemetry, mission tasks and plans can provide an at-a-glance summarization of current conditions. To that end, we have chosen an autonomics-based approach, a self-managing process, whereby a Command and Control (C2) scenario is formally modelled and thresholds for acceptable mission plan and global values are established and evaluated. A screenshot of Plan Monitor information is shown in Figure 5-45.

With autonomics selected as our technical approach, our next step was to establish the communication and translation of the data into model components. Due to the complexity of the plans, and in order avoid the time-consuming task of manually creating models, we developed a mechanism to dynamically generate model

components from the system data. Configuring these models with templates defined a priori, we established plan health and global constraint evaluation. Finally, an HMI was developed in which a pattern of Working Agreements was explored.

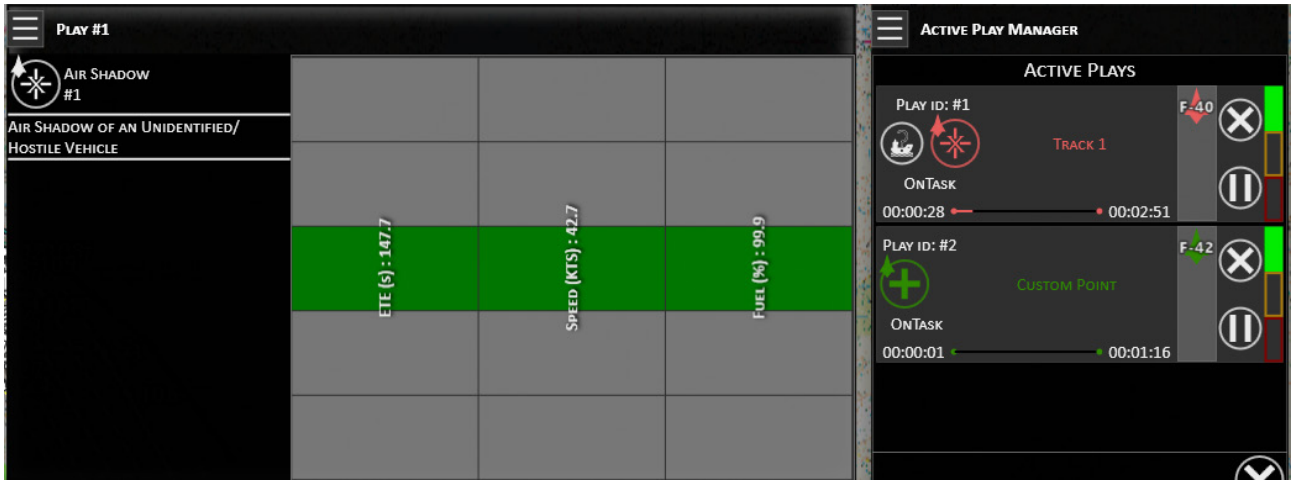

Figure 5-45: Plan Monitoring in IMPACT. The figure shows performance of vehicles relative to key play constraints as monitored by the IMPACT Plan Monitor.

Since the purpose of Plan Monitor is to provide feedback on the live monitoring of plans and anomalies, we chose to use an autonomics approach. Inspired by the human immune system, autonomics can monitor a system's attributes to provide an automated response when an undesired system state is detected. Plan Monitor leverages the Rainbow Autonomics Framework, developed at Carnegie Mellon University, which enables autonomous management of networks through:

- The ability to dynamically monitor and analyze a network's properties;
- The ability to detect breaches on a network's architectural design assumptions; and
- The ability to effect changes on a network in response to breaches in design assumptions.

Rainbow grants software architects the ability to establish a model of a network through the use of Acme, a formal architectural design language [143]. The model reflects network properties and rules enforce a network's design assumptions. Rainbow's probes and gauges dynamically translate the state of the network into the model while strategies, tactics and effectors provided automated adaptation to effect changes on the network. A key observation was that the structure of a plan allows plans to be represented as networks thereby granting the ability to manage plans with Rainbow.

Since Rainbow is written in the Java programming language, Plan Monitor was developed in Groovy, a superset language of Java. Its software elements are as follows:

- Model:
  - Establishes components representing vehicles, tasks, areas of interests and zones.
  - Establishes components representing plans by connecting the components above to reflect plan structure.
  - Establishes templates, rules and thresholds ensuring the integrity of plans.

- Probes subscribe to network hub and ingest relevant messages. Report data to appropriate gauges.
- Gauges:
  - Update components and properties in the model. May provide additional data processing.
  - Employ method to dynamically generate model components from network hub messages.
- Strategies and Tactics:
  - Call effectors to act upon detection of poor plan health.
  - Call effectors to act upon global constraint breaches.
- Effectors:
  - Publish plan health for display to the operator.
  - Publish constraint violation notifications for display to the operator.

5.10.2 Summary of Any NATO Communications/Collaborations/Interactions

Collaborations between the US members of the team and those from the Netherlands (Marc Neerincx), Germany (Axel Schulte and Diana Donath), and the UK (Antony Grabham, Robert Taylor, and Helen Keirl) informed our task manager and plan monitor work in regards to the employment of the working agreement pattern in particular.

	Planning/Design	**Execution**	**Analysis**
Communication	*Germany, Netherlands, UK*		
Coordination		*Germany, Netherlands*	*UK, Germany*
Collaboration	*USA*		

5.10.3 Future Research Needs and Plans in This Area

The incorporation of patterns such as working agreements and increased urgency and those related or chained to them in some way will provide significant benefits in the future. For that reason, the opportunity to continue to collaborate with the people and organizations mentioned in the section above would be invaluable

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Chapter 6 – CONCLUSIONS

Leo van Breda
TNO
THE NETHERLANDS

Timothy Barry
Ball Aerospace
UNITED STATES

Task Group (TG) HFM-247 successfully developed and demonstrated pertinent Human-Agent-Robot Teamwork (HART) systems, based on progress in Robotics, Artificial Intelligence and Human Performance Modelling. In these HART systems, humans and autonomy dynamically adjust and cooperate to accomplish a joint objective, often in shared spaces. In these systems, team members' responsibilities and commitments are managed such that the human and automation jointly enhance performance and manage contingencies. In a series of ten specific Technology Activities (TAs) the TG attempted to identify and formally describe common grounds among researchers to adhere to the term "Human-Autonomy Teaming (HAT)" to describe systems in which humans work with highly automated agents. Where those agents carry attributes like "autonomous" or "intelligent", we assigned the unified term "cognitive agent" in this nomenclature. In that respect the TG established a procedure and a common language to describe concepts of HAT with the goal to contribute to a more objective debate, to facilitate the effective communication between researchers, and to provide guidance to practitioners.

A variety of important issues were addressed such as agreement on a common system-level framework pattern approach, HAT performance metrics, and possible solutions focused on dialog management, working agreements, transparency, and explicit intent communication. During the TAs, HFM-247 also concentrated on the identification and demonstration of successful HAT applications, methodologies and design practices for HAT.

Based on these TAs the following conclusions can be drawn:

- Live demonstration of HAT concepts and enabling technology as experienced within NATO HFM-247 is a complex undertaking which requires serious preparation. These TAs were well received by the entire Task Group. (See all chapters.)
- These TAs, along with periodic meetings, provided a valuable forum to exchange technical information and discuss possible future collaborations in HAT design method research and concept development. (See all chapters.)
- This TG addressed the very real difficulties associated with generalizing HAT solutions from one application to another through an exploration of design patterns. Design patterns have proven to be successful in the human-computer interaction and software engineering domains, so the group decided to examine if this concept could be leveraged for use in HAT applications, i.e., to provide a common structure and vocabulary for relating each other's HAT artifacts. The core idea was to identify reoccurring problems faced in HAT applications, and then propose a few candidate HAT solutions that might serve as design pattern instantiations. This promising effort needs more research before a judgement can be made as to the utility of this approach. The initial motivation and approach taken were described, as well as some candidate HAT patterns for continued assessment.

  This TG also identified research priorities for continued research in this important area. The group ranked a list of candidate challenges in terms of perceived importance, and the resulting list was linked via a conceptual mapping.

  As a means to disseminate the results and lessons learned from this TG, a NATO symposium (HFM-RSY-300) was organized at the end of this effort. This symposium included presentations and demonstrations of selected TAs conducted throughout the TG period. (See Chapter 1.)

- This TG especially worked on defining abstract patterns which could be considered as solutions to the main challenges related to the introduction of an artificial agent within a collective of human teams. Relationships between Team taxonomy features, Scientific Challenges and Patterns are explained: Working agreement, Dialog management, Transparency, Explicit intent communication, and Increasing urgency and adaptive automation. (See Section 2.1.)
- Clearly there are a wide range of HAT challenges that will need to be resolved in order to maximize operational interactions with increasingly intelligent military systems. Some challenges will matter more and some less, depending upon the particular mission application and level of autonomy involved. However, all focus on properly designing the human touchpoints to these systems in order to maximize flexible, safe, and efficient operations. (See Section 2.2.)
- The metric portfolios reported in the separate Technical Activities (TAs) demonstrate a large variety in the functional subsystems that they addressed. However, all TAs report that they employ a portfolio of combined outcome, process, and properties of the functional systems that make up human-autonomy teams. Relatively traditional human factors metrics are combined with more innovative metrics that focus on teaming aspects. Improvement potential for the portfolio of metrics of the TAs have been discussed. The use of metrics is however specific to the Technical Activities that focus on quite different tasks and functional systems, which makes the metrics difficult to compile and compare in a single comprehensive list, considering the risk of interpreting the use of the metrics out of their experimental context. This applies also to the reported lessons learned on what worked well and what could be improved in the TA metrics portfolios.

  However, the following list of may provide an indication of some of the ambitions and suggestions of HFM-247 participants' future use and employment of metrics in human-autonomy teaming studies:

  - Human-Autonomy Communication;
  - Human-Autonomy Trust (mentioned five times, incl. once "in real-time", once "over time");
  - Number of Courses of Action examined;
  - Verbal protocol;
  - Joy of use, user experience;
  - Team coherence; and
  - Team resilience. (See Section 2.3.)
- This TG describes the broad concepts and doctrine guiding the exploitation and military use of autonomy, and more specifically, Human-Autonomy Teaming (HAT). Technological limitations, legal and moral constraints, and most effective human involvement, suggest that some form of human-in-the-loop control always will be required. This means finding the right balance of human supervision and automation must be identified in context. In order to determine the level of supervision required to complete a mission, use cases can be used to test automation concepts in realistic scenarios. This report describes an endorsed scenario and three militarily relevant use cases, providing a representative, routine and stressing, military context of use for HAT concepts and technologies. The intention is to show where and how, by presenting specific examples of use, each national Technical Activities (TAs) or HAT design pattern can be applied and exploited for military benefit, with the ability to consider the strengths, weaknesses, opportunities and risks of HAT. (See Chapter 3.)
- Drawing from ideas presented in A Pattern Language (Alexander, Silverstein and Ishikawa, 1977), HFM-247 chose to use patterns to describe solutions found or proposed within the TAs. The goal is to

begin to create a NATO pattern catalog for HAT that can be built upon, allowing those within the alliance to share information. (See Section 4.1.)

- HFM-247 developed a common, easy to use nomenclature to describe highly automated human-machine systems in the realm of vehicle guidance and to foster the identification of established design patterns for human-autonomy teaming. With this effort, HFM-247 facilitated the discussion and exchange of approaches to the integration of humans with cognitive agents among researchers and system designers. In using this nomenclature, HFM-247 identified most important top-level design patterns, such as delegation and associate systems, as well as hybrid structures of humans working with cognitive agents. The authors describe a method for documenting Human-Autonomy Teaming (HAT) design patterns, following a strict top-down procedure inspired by systems engineering and cognitive ergonomics. Coming from a general human-systems view, we ended up at the level of frequently recurring actor-relationship-actor-tuples, which may serve as containers for similar or competing design patterns to be found, described, and discussed. However, the benefit of this approach heavily depends on the researchers' and practitioners' efforts to describe their solutions to HAT problems using the offered method. In doing so, we could avail of a great opportunity for rational discussions on future highly automated systems. (See Section 4.2.)
- Robust implementations of bi-directional communication between human and automation teams does not yet exist. As a preliminary implementation, HFM-247 conducted a simulation which incorporated bi-directional communication, among other proposed HAT tenants, into a ground station with an automated recommender system used by a ground operator to support multiple commercial aircraft in high workload and off-nominal situations. The automated recommender system was designed to support rapid diversion decisions for commercial pilots in off-nominal situations. To support bi-directional communication, we provided preset weights for each play (a play defined operator and automation tasks) and presented the weight settings to the operator. The operator was able to negotiate with the system by changing the weights to better fit the situation and could adjust the weights to see how the divert recommendation might be affected. For example, in a Medical Emergency play, more weight was given to the estimated time of arrival and services provided rather than fuel consumption. Participant feedback supported the use of weights to improve automation's ability to handle unusual situations and were useful in making divert decisions. (See Section 4.3.)
- The working agreement patterns described by the authors are mainly focused on negotiations and commitments between an autonomous agent and a human (UAV and airspace manager; or UxV and rescuer), supporting human-autonomy teaming where autonomy is giving the human information, and is asking for permission to complete a task. Other examples of negotiations between human and machine could be when handing over a track from one platform to another, handing over a platform from one user or controller to another or calling for a platform to undertake a specific task such as CAS or Casualty Evacuation (CASEVAC) 9-Line tasking requests.

  By evolving from human-human negotiations through human-autonomy negotiations and applying appropriate policy management for control of autonomy, implementation independent formalisms for future autonomy-autonomy negotiations can be matured that provide both trust and transparency to operators, as well as providing progressive safety evidence to regulatory authorities. (See Section 4.4.)
- The important advantage to using design patterns is that they can be adapted to inform multiple instantiations where human and agents interact. The Transparency pattern can be reused in contexts where information about the agents' reasoning process and projections/uncertainty is critical to human-agent team performance. The Situation Awareness-Based Agent Transparency (SAT) pattern has been used to develop and evaluate transparency displays for the Autonomous Squad Member

(ASM), a US Department of Defence Autonomy Research Pilot Initiative (ARPI) program as well as design information requirements for US Army Research Laboratory (ARL)'s Human-Robot Interaction research. (See Section 4.5.)

- The Explicit Intent Communication pattern seems to fit nicely into the proposed template and to offer reasonable, if somewhat abstract, advice to potential HAT designers. The augmentation of the representation schema including most of the solution patterns used by the TG seems to offer significant added value. (See Section 4.6.)
- A pattern that provides a means for an assistant/associate system to mitigate erroneous behavior of an operator by a stepwise increasing intervention/support was developed and demonstrated. The interventions of such an assistant/associate system ranges from alerts, messages, and suggestions up to overrides in order to transfer a dangerous situation into a normative (safe) one. A stepwise approach serves to keep the operator vigilant and responsible for task accomplishment. The pattern can make use of *working agreements* to establish the rules by which urgency will be addressed. The formalization takes features from a pattern that might be titled *tasks with deadlines and rewards*. In that pattern, rewards are only received in full if the task is completed prior to its deadline. This pattern has a complex interaction with the pattern *human takes control upon autonomy failure*. That pattern requires that a method requiring human attention be selected for a task that formerly was being performed by the autonomy and may cause an immediate increase in urgency. This may be how the user is notified of the need to take control (e.g., a new method is selected when the autonomy fails, this method requires urgent attention, so the task manager tries to reduce urgency by going to the autonomy). To avoid infinite loops, the methods allowing action by autonomy need to be marked as unavailable through some means. (See Section 4.7.)
- The TAPAS (Techniques d'Analyse du Partage d'Autorité des Systèmes de Systèmes / Analysis Techniques for Shared Authority in the Systems of Systems) experimental study examined configurations of multiple fighters in hybrid configurations composed of fighters *in combination with* a fully autonomous Unmanned Combat Air Vehicle (UCAV). The results revealed specific tasks of the fighter aircraft patrol collective work for which the Team Performance was weakened by a workload increase and/or a team interactions quality decreased. As a consequence, the COmmunication and WORKload analyses to study COllective WORK of fighter pilots (COWORK2) methodology can be used to evaluate, in a posteriori or real-time fashion, Team Performance of collective tasks. The application of the method especially showed that it could be very relevant to detect the collective tasks with reduced Team Performance at individual and team levels. The combination of the two complementary analyses, related to workload and communication, provides a reliable multicriteria means to classify tasks. (See Section 5.1.)
- A work system for the realization of scalable and adaptive autonomy was demonstrated and tested, applied to a manned-unmanned teaming setup, in which a manned helicopter crew uses multiple Unmanned Aerial Vehicles (UAVs) to fulfil a given mission (e.g., a Combat Recovery Mission). The task-based UAV-guidance, the sensor management and the task-centered associate system with the key aspects Mixed-Initiative Mission Planning, Pilot Observation, Activity Recognition, Resource Determination and Intervention Generation were implemented prototypical within the helicopter mission simulator of the Institute of Flight Systems at the University of German Armed Forces in Munich. Within the task model used, 226 tasks were represented, and 85 asks were possible to be detected by the activity recognition. The system for monitoring the pilots enabled the automatic observation of approximately 1300 measures. 440 of these observables were actual used for the activity recognition, which again generated 730 evidences. This means 8.6 evidences per task in average. The resource determination also took place online based on the detected activities/tasks of the pilots. Extensive simulator trials took place with helicopter pilots of the German Armed Forces. (See Section 5.2.)

- The applicability of the concept of interaction patterns was demonstrated in a Cooperative Guidance and Control task setting where a human operator worked together with a cooperative automation (e.g., a highly automated car can either assist the driver in maintaining an energy efficient state or may even take over more advanced driving tasks such as lateral and longitudinal control in varying degrees.) In the military domain, these aspects can be extended with system qualities like safety and survivability. When driving for a certain time in a convoy, the workload of many drivers can be reduced to only the workload of the leading vehicle driver, where the others can observe the environment for threats). An effective way to create cooperation between human and automation is that human and machine have the same internal model of what has happened, what is currently happening and what will happen (i.e., cognitive or inner compatibility). In the demonstrated model, compatibility results from implementing the structure of human planning and acting into the automation. On the human side perception works over the sensory modalities, whereas the automation needs suitable sensors. Situation assessment is the interpretation of the situation and its projection into the future. The next concrete steps to further prove the applicability of the concept of interaction patterns is a further refinement, e.g., to find good mappings between interaction elements from the source domain to a certain image schema and the respective internal target state in the target domain. (See Section 5.3.)
- Research in team situation awareness, agent transparency and trust calibration has been discussed and aligned with research at ARL, USA, resulting in the organization of a Workshop on Transparency at an international conference (RO-MAN2017), and in a special issue of the IEEE Transaction of Human-Machine Systems on Agent and System Transparency. The requirements, opportunities and constraints of AI Technology that can underpin ePartner's team abilities and behaviors have been explored with SPAWAR, USA. The general engineering and design pattern approach for HAT has been extensively discussed with UniBW, Germany. Further insight in the requirements of a general human-centered, cognitive work analysis and system engineering approach for HAT has been acquired in meetings with FOI, Sweden, particularly on the empirical grounding of the claims on agents' contribution to the team performance. (See Section 5.4.)
- Results of an exploratory interview study with personnel from the Swedish Armed Forces regarding the aspects of Command and Control (C2) and cooperation between human operators and autonomous systems show that the Swedish Armed Forces personnel are well aware of the capabilities and benefits that can be gained by autonomous systems. Several examples were discussed where the expected benefits consist of, for example, new tasking possibilities, increased efficiency, less exposure to risks for personnel, and increased possibilities for actions in high risk areas. The areas discussed in relation to C2 of autonomous systems were, amongst others, navigation, tasking and collection of sensor data, force protection, weapons systems, communications and IT systems. Many of the automated functions that were discussed related to sensors, navigation, communications and IT systems are already operational or likely to be operational in the near future, while the automation of weapons systems for increased effect is seen as the most problematic function, also from a C2 perspective.

  A technical autonomous capability is however not enough to achieve the expected benefits. In order to make autonomous systems work in coordination with manned systems, the operator needs to understand, for example, which factors affect system behavior, especially in the case of coordination within a team of manned and unmanned units that need to follow common doctrines. Several of the interviewees also mentioned and exemplified the potential increase in battle complexity and tempo when combinations of competent autonomous systems would be used. This could lead to an increase in the level of difficulty in terms of controlling the executed actions, as control of complex systems demands an understanding of an increasing amount of mutual functional interdependencies and possible interactions between coordinating units. Furthermore, the inherent dynamics of combat and the potential

unpredictability of the autonomous systems behavior as part of a complex system constitute crucial challenges. According to the majority of interviewees, the control of autonomous systems requires among other things the possibility to flexibly define:

1) Which functions and capabilities should be autonomous;
2) Which roles should control these capabilities; and
3) Which functions should adapt or be adapted to form capabilities when confronted with unpredicted or degraded circumstances.

The 'capability cards' that were used during the interviews generally worked well as a starting point for a general discussion about higher degrees of automation within defence systems. Furthermore, future studies are recommended to address the purpose, benefits and risks with automation and "autonomy" of *functions* or *capabilities* (as was done in this study) in order to avoid a purely technologically driven development dialog. In future studies, there are also possible benefits with identifying further challenges related to problems specific for command and control systems. This can be achieved by employing more concrete scenarios and technical solutions in order to enable mapping of possible variations in the operational environments and corresponding ability and technology solutions that answer to the expected degree of military benefits. Future studies therefore need to combine participants with different backgrounds, for example by having diverse Armed Forces roles participate in different study phases. This will enable an appropriate match between criteria and actual needs for future autonomous systems.

The interaction between various C2 levels, flexible roles and flexible "autonomous" functions is deemed to be of significant importance, along with the formulation of a common doctrine and C2 systems for the use of autonomous systems. Systems understanding is to be considered as important for enabling effective and efficient use of these systems. How to design for observability, predictability, and directability needs to be investigated. The use of autonomous systems will affect all stages of future systems development and procurement. Today's systems development approaches are not explicitly designed to consider the potential interactions that can emerge within and between systems with autonomous capabilities. Thus, this area must be given sufficient attention in order to design and implement automated functions and co-adapt organizations, doctrine, methods, and C2 in order to gain the intended benefits and to manage the risks of automated and unmanned systems. (See Section 5.5.)

- Under NATO TG HFM-247 HAT, a technical workshop on HAT metrics was held in Farnborough UK on 7 Nov 2016. The workshop was well attended by 11 NATO HAT researchers, with participation from UK, US, Sweden and Germany. The UK research on HAT metrics was fully briefed and discussed in depth. The meeting identified requirements for HAT framing cycles, internal/external performance parameters, veracity and rationality, with a "deep dive" into metrics for policy rationality, negotiation and working agreement patterns. It was agreed that good progress had been made on developing HAT metrics, but that further research was needed to develop understanding of the requirements for, and provide proof of the military benefits of, Human-Autonomy Teamwork vs. Human or Automation Teamwork. (See Section 5.6.)
- Subjective and behavioral indicators of HAT collaborations were examined using a proof-of-concept demonstration of HAT tenets: bi-directional communication between the human and automation, transparency for automation, and an operator directed interface. Because this was primarily a demonstration, the low number of participants resulted in limited statistical power. Nevertheless, the collected data suggest both the potential advantages and disadvantages of HAT.

  Overall, participant feedback was positive, supporting our implementation of HAT features. Participants liked having a recommender system with factors and weights and expressed interest in having similar

automation for real flights. They valued the integration of the displays, commenting that this level of integration is not currently available. Participants found the electronic checklist useful as were a number of the alerts.

Operator workload appears to be lower in the HAT condition and decreased with time in the scenario. Seeing that participants completed only one scenario with the HAT agent, this may point to the need for additional training. In the No HAT condition, workload was higher and roughly constant throughout.

Interestingly, while workload was rated lower, participants took more time to uplink flight plan changes in the HAT condition, even when no weighting adjustments were made. Typically, longer task times indicate higher workload. However, given that workload overall was very low, and that very few flight plan changes were made in each scenario, it is possible that the increases in event times were insufficient to change subjective workload. If this is the case, we speculate that in the HAT condition, providing an opportunity to alter the recommendations of the HAT agent led participants to consider the initial recommendations more carefully before either accepting or adjusting them. In the No HAT condition, if participants rejected recommendations of the ACFP, they would have to create a flight deviation with no automation assistance, and this may have led participants to accept recommendations with less prior evaluation. Of course, these speculations must be verified with further research.

These findings point out the difficulty in establishing behavioral and performance metrics for evaluating the effectiveness of HAT collaborations. On the one hand, longer event times might indicate higher workload and less efficient operations. Alternatively, longer event times might indicate more thorough processing, indicating that the HAT agent is improving operator and system performance. Understanding the effect of HAT agents on operator performance and the quality of HAT collaboration requires methods and measures be carefully developed and tested. We offer the following recommendations in this regard:

- Evaluations of HAT must be performed at all levels of the system, while using a battery of assessment techniques.
- Evaluations must include system, autonomous agent, and operator performance as well as behavioral precursors to operator performance. The latter measures include workload, situation awareness and trust in automation.
- HAT evaluations should also utilize subjective, behavioral and performance measures of effectiveness. Subjective measures are simplest; they can be administered at different times during a scenario and capture the operator's perspective on the construct of interest. Note that, in the preliminary evaluation of the HAT agent for Rescued Crew Operations (RCO), weight adjustments were made primarily by only one of the six participants. Validated subjective measures of HAT effectiveness are currently unavailable; however, validated subjective measures of human-human collaborations do exist, and they represent a reasonable starting point in this regard.
- Finally, performance measures of HAT effectiveness will necessitate carefully designed tasks and scenarios that are sensitive to differences brought about by a HAT agent.

Work is continued on the implementation of our HAT tenets. In particular, in the current implementation, plays were flat, including only simple checklists. Work is currently done towards making these more flexible with varying levels of automation, branch points, and opportunities for bi-directional communication. The goal is to develop a framework for HAT, consisting of tenets and guidelines for implementing them. Hopefully, software libraries will be created that make this implementation easier. (See Section 5.7.)

- The US Department of Defence's Autonomy Research Pilot Initiative (IMPACT) project produced significant knowledge in a number of areas important to autonomy-related capabilities. Not only did the project spur advancements in component technology development, model development, and general design understanding/guidance, but much was learned from the formal integration of key autonomy-related technologies into a single multi-UxV control station application. IMPACT also produced a robust "virtual lab" for continued human-autonomy teaming research. A three-station system (C2, Sensor Operator (SO), and Test Operator Console (TOC)) is available for organic wide-spectrum Human-Autonomy Teaming (HAT) evaluations with sites currently at the US Air Force Research Lab, the Space and Naval Warfare Systems Command, and the Army Research Lab. A new vision for future human-autonomy systems was successfully conveyed to DoD senior leadership via many interactive demonstrations of the IMPACT system. This vision clearly illustrates that the human will continue to have a prominent role in interacting with increasingly autonomous technology, dynamically flexing between supervisor, teammate, or manual controller as conditions dictate. Finally, IMPACT technologies have extended/transitioned in a myriad of ways. Other projects have leveraged IMPACT technology to advance their aims while new DoD projects and several industry contractors now utilize IMPACT in autonomy technology development efforts. Additionally, IMPACT has become the core C2 autonomy piece within an international Autonomy Strategic Challenge project which is a three-year, five-nation effort to integrate and assess promising allied autonomy capability in mixed live/virtual multi-UxV littoral environments. The IMPACT project has enabled a deeper exploration into the critical issues that influence flexible and effective human-autonomy collaboration. Although the IMPACT evaluation demonstrated military utility in several aspects related to operator-autonomy teaming, several deficiencies and gaps in understanding were also identified and improvements are underway. These include research related to novel methods for enabling bi-directional communication and management of temporal constraints, more naturalistic dialog and sketch interactions, and consideration of information degradation and uncertainty in decision-making tasks. Additionally, research is investigating the effects of a decentralized re-planning capability, real-time operator functional state assessment, and alternative team structures on overall human-autonomy teaming. Finally, additional technologies such as policy management and a narrative explanatory capability are being integrated with IMPACT capabilities for an international live-virtual military demonstration of human-autonomy teaming. The results of these follow-on efforts will provide a much richer understanding of this area. (See Section 5.8.)

  Results of studies as part of the IMPACT program to investigate the utility of transparency in Human-Autonomy Teaming, as well as best practices for implementing information transparency as part of an intelligent agent's interface confirmed that:

  1) Agent transparency, as operationalized and implemented using a Situation Awareness-Based Agent Transparency (SAT) model, is useful for improving performance in complex decision making such as that done in multi-UxV management tasks. Additionally, this performance is increased without a cost to workload. However, it should be noted that response time does increase for a few seconds, which may or may not create an issue depending on the mission environments. Overall, increased levels of transparency led to partially increased trust (in specific capabilities of the intelligent agent), while the effects of uncertainty information on operator trust are not always consistent; and

  2) Additional research is needed which explores human-agent teaming in a more bi-directional manner. Future studies will examine human-agent teaming with bi-directional communications to evaluate the utility of SAT-based interfaces in a dynamic manner. This can be used to inform the design of field research being done with finalized intelligent agents that are capable of behaving

independently. Additional efforts will also focus on developing a repository of user interface design elements (e.g., visualizations) to support SAT-based interfaces, while utilizing the IMPACT testbed. (See Section 5.9.)

- With the onset of a high volume of tasks, tasking can easily become overwhelming and disorganized, leading the operator to become less effective and focused in completing assigned tasks. To address these issues, as part of the Intelligent Multi-UxV Planner study within Adaptive Collaborative/Control Technologies part of IMPACT, a management system capable of determining user tasks was developed, dividing tasks into a hierarchy, presenting tasks to the user, and providing a mechanism to execute an action for each task. Based on this study it was concluded that the incorporation of patterns such as working agreements and increased urgency and those related or chained to them in some way will provide significant benefits in future developments. For that reason, the opportunity to continue to collaborate with the current people and organizations would be invaluable. (See Section 5.10.)

All TAs were very successful and well received by the Task Group members. It is therefore recommended to disseminate results and lessons learned associated with the activities of Task Group HFM-247.

Chapter 7 – WAY AHEAD

Mark A. Neerincx
TNO, Perceptual and Cognitive Systems
THE NETHERLANDS

Mark H Draper
711HPW/RHC, Air Force Research Laboratory
UNITED STATES

7.1 CONCLUDING THOUGHTS

The broad theme of the HFM-247 group "Human-Autonomy Teaming" (HAT) is even now becoming realized due to recent developments in technology and society. The technological potential for autonomy is increasing substantially, driven by the vast progress and investments in Artificial Intelligence (particularly Machine Learning) and other technologies like Robotics, Cloud Computing, Conversational Agents, Mixed Reality, Internet of Things and Sensing. Furthermore, the power ratio dynamics, polarization growths and increases of information processes in society are setting high demands for defence, safety and security operations, asking for highly adaptive capabilities of the evolving Human-Autonomy Teams. This report provided an overview of NATO countries' research efforts to develop these capabilities in a human-centered way, aiming at enhanced team performance and resilience for a safe society. Key results were the development of a common specification of HAT patterns and an overview of team metrics, as presented in the concerning chapters.

Whereas the HAT theme was actual at the start of the HFM-247 group, it has even become more actual since (e.g., Ref. [1]). So, this report can be viewed as a starting point for the research and development of human-autonomy teams, which consists of human and machine team members. Ever-smarter AI technology is being developed and will be further developed for a prolonged period. Giving responsible and effective direction to this development, *and* to its uptake into defence systems and military missions, is crucial.

In general, this development will change the way in which the missions are carried out by the human-machine teams. On one side, the AI adds new capabilities and skills to the team, but, at the other side, it has still some several fundamental limitations – such as making sense out of data from a new situation – which constrains deployment of full autonomy (e.g., Ref. [2]). By aiming at a complementarity in hybrid human-AI teams, strengths and weaknesses are being supplemented and compensated. In such teams, humans and AI are mutually adaptive (learning) agents. To guide the joint, interdependent, adaptation and learning processes, the development of the human-AI system is a continuous (iterative) process, assessing and directing the learning and performance [3]. Joint task performance of human and machine agents requires that their social, cognitive, affective and physical behaviors are harmonized for the work processes in a fundamental way [4]. For establishing such harmonization, Johnson et al. [5] identified three principles: *observability*, *predictability*, and *directability*. In addition, recently, *explainability* has been recognized as a fourth principle for responsible and effective collaboration in a hybrid team (e.g., Ref. [6], [7]).

In the 10 Technology Activities (TAs) of the HFM-247 TG, these four principles have been partially addressed. Starting with a common method to describe ("language") the interdependent (design) patterns of agents' work processes in a team [8], the actual HAT research topics, activities, and plans were identified and related to each other. This way, at different levels of cooperation research progress was made and shared, e.g., on dialog management, work agreements, transparency, explicit intent communication, and HAT performance metrics. This report provided the overview of the research scope and progress made. In the next section, we will briefly enumerate some remaining challenges that we are facing for developing the desired human-AI systems for responsible and effective teamwork.

7.2 CHALLENGES

The following six challenges for the research and development of responsible and effective Human-AI teamwork are described separately. It should be noted that they are related to each other and can be investigated in (partial) combination:

1) **Team Design Patterns for Dynamic Evolving Behaviors**. Design patterns have been recognized as an important tool to abstract from local design solutions in order to share, relate and re-use the "generic" knowledge about design solutions. Team design patterns haven been proposed and presented in this report (e.g., Ref. [9], [10], [8]). However, these approaches hardly address the continual development of teams, i.e., the practice of evolving resilience and effective performances. Such work practices are established over time after a series of possibly diverse (team) experiences. Recently, Van Diggelen et al. [11] proposed a framework for the development of a library of team design patterns that addresses the dynamic team behavior at both the team and individual level explicitly. A HAT ontology underpins the team design patterns so that the design problem and solution can be specified univocally. These patterns can be used *at design time* (i.e., to integrate proven patterns into the behaviors of artificial team members) and *during operations* (i.e., to stimulate beneficial patterns and mitigate appearing problems). It will be a major challenge is to work jointly on the development, validation and maintenance of the proposed pattern library, which should contain actual proven models and methods to advance the human-agent teamwork.

2) **Continuous Trust Calibration**. Longitudinal trust development, repair and calibration are crucial for resilient and effective teamwork and, consequently, have been studied in different research projects (e.g., Ref. [12]). It is inherently difficult to systematically address the team and longitudinal aspects for realistic work settings. For this, we need a model that predicts the reciprocal effects of trust and teamwork, and can help to establish adequate trust calibration [13]. Also, increasing the focus from trust itself (a mediating psychological construct) towards appropriate reliance (measurable behavioral outputs) will facilitate the development of useable design guidelines.

3) **Scope Enlargement**. In this report, the HAT scenarios do not cover all relevant characteristics of future team demands of defence organization. For example, automation (particularly AI) will have a major impact in (near) future cyber operations, asking for responsible and effective human-AI collaborations within the teams (e.g., Ref. [14]). The scope of future investigations should be expanded to cover all relevant teaming structures and characteristics.

4) **Meaningful Human Control**. The concept or "partnership" can be applied to establish explicit, value-sensitive and flexible control of team members' (i.e., the "partner") activities [15], [16]. As partners, team members need to acquire and show understanding of the meaning, weighting and implementation method of the joint goals they are committed to. This type of understanding and commitment is being built and communicated via three partnership interactions in Human-Agent Teams concerning Objectives, Work Agreements and Explanations (see Figure 7-1). First, active partnerships require the setting, progress monitoring, refinement and adjustment of joint *objectives*, based on a shared understanding, awareness and communication of the objectives and their situated urgencies. Stakeholders' values, strategic intentions and momentary context conditions determine the urgency and feasibility of the objectives to pursue. The choices of the objectives can require re-assessment and adjustment to deal with changing circumstances, possibly just in advance or even during the work processes. Second, the proposed human-agent partnerships involve explicit, univocal and possibly adjustable, *Work Agreements (WA)* on how the tasks should be allocated and performed [17]. Similar to the modelling of the objectives, an ontology design pattern has been developed for work agreements, defining the knowledge required for a team member to set, reason about and adjust work agreements.

The WA-ontology defines core concepts with their relations encompassing the knowledge to specify, activate, monitor, and reason about work agreements: ***<creditor, debtor, antecedent, consequent, lifespan, acceptance>*** [18]. Third, *explanation* models for ePartners are developed that should invoke adequate trust calibration (i.e., to mitigate over- or under-reliance) and improve the learning of the team members (see next challenge 5). It will be a major challenge to instantiate the partnership models for realistic complex teamwork, and test their effects on team performance and resilience. Future NATO activities should explore the very complex yet critically necessary need for establishing and maintaining meaningful human control across the wide variety of future AI applications (i.e., beyond unmanned system applications).

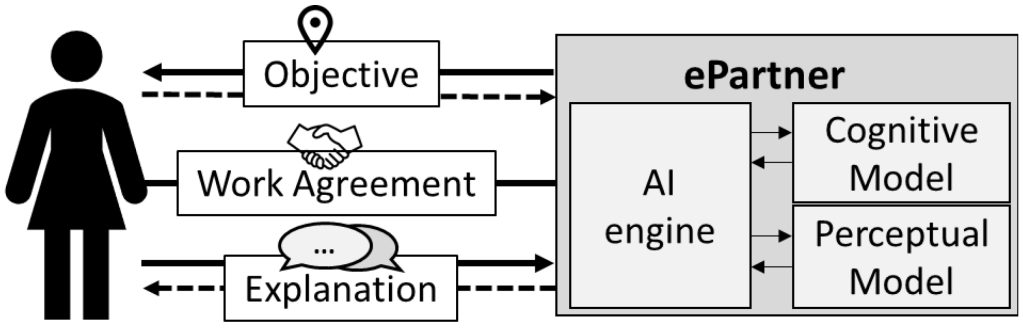

Figure 7-1: Three Human-Agent Partnership Interactions: Objective Sharing, Harmonizing Activities via Work Agreements and Explaining Task Outcomes.

5) **Explainable AI in Human-Agent Teamwork**. Recently, large research projects on explainable AI (XAI) started, often from a more technological perspective with a "one-shot" dyadic AI-human interaction [19]. So far, less attention is paid to the development of explanations in human-agent teams, for which a more integrative approach is needed. For this, Neerincx et al. [15] proposed a Perceptual-Cognitive eXplanation (PeCoX) framework for explanation generation, communication and reception, which addresses both the perceptual and cognitive foundations of an agent's behavior. Two challenges have been identified for establishing XAI models and methods that enhance the human-agent teamwork, including a computational theory of mind that helps to realize the required personalization, and a model- and data-driven mechanism for selecting the appropriate explanation method like contrastive or example-based explanations [20], [21]. This and other proposals for explainable AI need to be further explored to facilitate trust calibration and appropriate reliance.

6) **Evolving Hybrid Intelligence by Co-Learning**. The cooperation of humans and machines in a hybrid human-machine team sets new demands as the nature of intelligence is different between agents [22]. For the cooperation, we need models that facilitate processes that allow the hybrid teams to learn from training and operational experiences. Both human and machine actors should be able to feed and to consult the models in such a way that it contributes to the team performance.

7.3 NEW NATO GROUPS

Recently, two new NATO groups started to explore some of the challenges as a joint NATO effort:

- **NATO HFM-ET-178.** An Exploratory Team has been started to investigate possible approaches, research directions and collaborations on Meaningful Human Control (*challenge 5*). One objective is to develop a definition of MHC not only for the current activity but also to be proposed for broader use within NATO. MHC will be examined from multiple perspectives:

1) Authority, responsibility and accountability in the chain of command, including legal aspects;
2) The type of application;
3) The type of interaction between humans and AI-based systems, ranging from oversight over systems to coordination with systems or collaboration with systems; and
4) Mediating characteristics and factors associated with MHC.

- **NATO NIAG SG-233.** This Industry Advisory Group is providing an industry perspective on Human-Machine Teaming. The group studies the integration of human factors in the development and implementation of future decision support systems.

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Manned-unmanned teaming
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14. Abstract

Ongoing technology-driven evolution of automated uninhabited systems (e.g., incorporating artificial intelligence and cloud computing) set the focus of the HFM-247 activities on Human-Autonomy Teaming (HAT): The identification, validation and demonstration of methodologies and interaction design practices that allow for shared situation awareness of task and environment, bi-directional understanding of intent, dynamic work distributions, goal-directed communications, and effective mission collaboration in HAT. HFM-247 developed and applied an "empirical pattern" approach to explore creative solutions in key application areas and establish harmonization of activities within the group: Each participating nation identified at least one HAT-related Technical Activity (TA) being conducted within that nation, relating it to the pattern concepts and evaluation metrics. The resulting 10 TAs showed common human factors and design pattern elements. This report summarizes the HAT approach and TAs with the lessons learned and the recommendation to focus research on meaningful human control, continuous trust-calibration for reliance on automation, explainable Artificial Intelligence in human-agent teaming, and evolving hybrid intelligence by co-learning.

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