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Conceptual Modeling for the Probability of Raid Annihilation (P_{RA}) Testbed

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ABSTRACT*: A U.S. Navy enterprise methodology has been established for consistent ship self defense operational test and evaluation (OT&E) across all ship classes. A cornerstone of the Navy T&E Enterprise is the Probability of Raid Annihilation (P_{RA}) Testbed. The Navy P_{RA} Testbed implements HLA federated simulations of ship combat system elements against independent, reactive threat raids in a common environment to formulate an overall combat system assessment. The LPD 17 ship class is the first to implement a P_{RA} Testbed baseline as a formal component of ship class OT&E. Products and lessons from the LPD 17 baseline are being transitioned to multiple ship classes including DDG 1000, LHA 6, LCS, and CVN 21.*

While the P_{RA} Testbed LPD 17 baseline adheres to the Federation Development and Execution Process (FEDEP), conceptual modeling is a particularly distinctive feature. The Systems Engineering Concept Model (SECM) is an extension of the 'Conceptual Model' product of FEDEP step 2 that broadens the impact of conceptual modeling in the SE process and specifically supports federation Verification, Validation, and Accreditation (VV&A). Accreditation of the P_{RA} Testbed for LPD 17 operational testing is a challenging proposition. The purpose of the SECM is to provide a central documentation tool for stakeholders to 'view' the Testbed capabilities and limitations from multiple perspectives.

The SECM is divided into 3 views, which generally follow sequential stages in Testbed system engineering: System View, Model View, and Federate View. Each view is intended to reveal, address, and resolve a particular class of issues for P_{RA} Testbed accreditation. Explanation of engineering judgments is inclusive to the documentation. The SECM is a not an 'easy button' for making engineering decisions or wishing away limitations. Yet, it does create a framework of deliberate intent for making decisions and accountability for limits in capability. The SECM also establishes a persistent documentation product that feeds the corporate knowledge base for subsequent ship classes.

During SECM development many lessons have been learned about conceptual modeling. In this paper, we venture to share those lessons learned and describe how we overcame the trials and tribulations of documenting engineering level details in the SECM for the P_{RA} Testbed LPD 17 baseline.

1. Introduction

The U.S. Navy has moved to more of an 'enterprise' approach to conduct developmental and operational testing for Ship Self Defense. This effort endeavors to eliminate or decrease duplication in both testing and model development. It also endeavors to increase re-use of tools and simulation frameworks to decrease developmental and operational testing cost for the Navy. The enterprise approach to T&E has been formalized in a Capstone Enterprise Air Warfare Ship Self Defense (AW SSD) Enterprise Test and Evaluation Master Plan (TEMP)[1]. The SSD

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Enterprise TEMP was drafted during mid-FY06 and has been signed by the Program Executive Officer, Integrated Warfare Systems (PEO IWS) and the Navy's Commander, Operational Test and Evaluation Force (COTF).

2. Ship Self Defense T&E Enterprise

The Ship Class Anti-Air Warfare (AAW) Self-Defense Capstone Requirements Document (CRD) of 5 Feb 1996 defines a Probability of Raid Annihilation (P_{RA}) requirement against Anti-Ship Cruise Missiles (ASCM) for surface ships[2]. The requirement applies to several new ship classes, including LPD 17, LHA 6, DDG 1000, CVN 21, and the Littoral Combat Ship (LCS).

Meeting P_{RA} requirements involves a significant amount of ship and combat systems level T&E. In addition, individual Combat System Element Program Offices have specific AW SSD T&E requirements to evaluate proper combat functionality and performance against Anti-ship Cruise Missile (ASCM) threats[2]. Integrated ship self defense performance assessment poses certain distinct challenges to the T&E community. Among them are short range hardkill engagements and integrated hardkill/softkill engagements, both against multi-threat ASCM presentations. The confluence of issues results in no live test venue being able to fully address end-to-end performance of the complete combat system. Hence, M&S is needed to augment live results and formulate the overall combat system P_{RA} assessment.

The Enterprise TEMP consolidates testing across ship classes according to combat system variants vice platforms and implements M&S in Navy surface ship operational testing at an unprecedented level. The Enterprise TEMP pursues culture change in Navy T&E by indoctrinating P_{RA} Testbed simulation events as formal test events in the Enterprise TEMP. Further, the Enterprise TEMP coordinates the M&S events with a carefully planned series of empirical test events across the combat system variants and ship classes. Centralized planning ensures adequate live testing to validate the models and assess performance without redundant testing.

2.1 Enterprise PRA Testbed

A cornerstone of the Navy T&E Enterprise is the P_{RA} Testbed. The Navy P_{RA} Testbed implements High Level Architecture (HLA) federated simulations of ship combat system elements against independent, reactive threat raids in a common environment to formulate an overall combat system performance assessment[3].

PEO IWS is responsible for ensuring consistency and continuity of the assessment process and its associated simulation framework. The simulation framework that guides P_{RA} Testbed development is governed by the following top-level requirements:

1. Interoperable simulations on a single runtime infrastructure
2. All system representations execute simultaneously for each ship defense engagement
3. Common threat and natural environment achieved via unified modeling, distributed execution
4. System-to-system communications should be Interface Design Specification (IDS) compliant
5. System-to-system interactions (e.g., signal propagations, emissions detections) should be physics-based through the common environment
6. Representation detail must be of sufficient detail for use in Operational Test and Evaluation (OT&E).

The functional components of a P_{RA} Testbed baseline are depicted in Figure 1. The P_{RA} Testbed architecture provides simulation runtime mechanisms for interfacing combat system element simulations, implementing common threat and environment representations, and realizing integrated hardkill/softkill scenarios. Each component must provide representation of sufficient detail to achieve accreditation for use in testing. Specific simulation requirements for particular components are resolved during the Testbed baseline system engineering process.

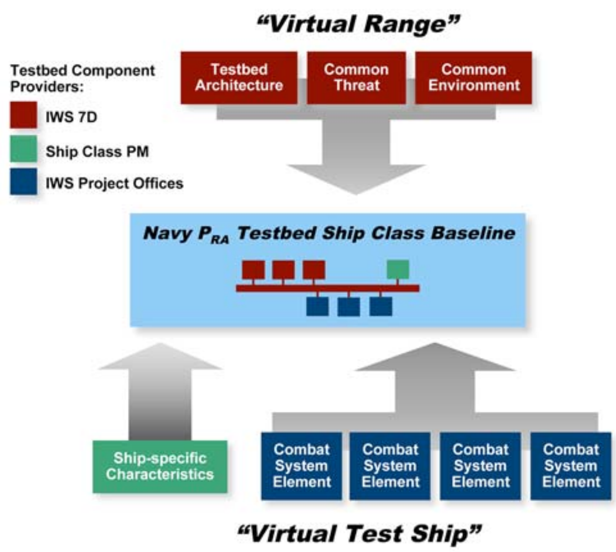

Figure 1. P_{RA} Testbed Components

P_{RA} is assessed by executing the virtual ship/platform within the virtual range across an array of scenarios and threat types. Each execution of the P_{RA} Testbed yields the result for one threat raid engagement. A matrix of runs across the span of scenarios and threat types yields the overall P_{RA} score. The simulations are validated with live test events including: land-based testing, laboratory tests, element-level tests, at-sea testing with the Operational Ship, and at-sea testing with the Self Defense Test Ship (SDTS).

A baseline of the P_{RA} Testbed will be implemented for each unique new ship class combat system configuration. Specific test planning for each P_{RA} Testbed baseline implementation is described in Section III of the SSD Enterprise TEMP[2]. The LPD 17 ship class is the first to implement a P_{RA} Testbed baseline as a formal component of ship class operational test & evaluation. Simulation products and lessons from the LPD 17 baseline are being transitioned to follow-on ship classes, dramatically reducing risk and cost of ship class operational evaluation.

3. The Systems Engineering Concept Model

P_{RA} Testbed systems engineering follows the IEEE 1516 standard Federation Development and Execution Process (FEDEP) for High Level Architecture (HLA) simulation. The Systems Engineering Concept Model (SECM) is an extension of the 'Conceptual Model' product of the early stages of the Testbed system engineering process. The SECM establishes a persistent documentation product that broadens the impact of conceptual modeling further in the SE process and specifically supports federation Verification, Validation, and Accreditation (VV&A). The SECM also provides a mechanism to examine shared modeling responsibilities (e.g., threat, natural environment) and understand migration of 'stand alone' legacy models to the P_{RA} Testbed federation.

A number of factors combined to incite development of the SECM as a documentation tool to support accreditation of the P_{RA} Testbed:

- The ship self defense problem space is complex
- Systems performance for P_{RA} assessment span across different technical communities and multiple managing program offices
- P_{RA} will be assessed using a federation of interoperable simulations; it will not (cannot) be tested empirically
- Many specific parameters, assumptions, limitations, etc. are negotiated between the testing and acquisition communities
- The testing community is intent on consistent P_{RA} assessment across ship classes and combat system configurations.

Accreditation of the P_{RA} Testbed for use in Operational Test and Evaluation is a challenging proposition. The purpose of the SECM is to provide a central documentation tool for stakeholders to 'view' the Testbed capabilities and limitations from multiple perspectives. Stakeholders include: COTF, the DoD's Director of Test & Evaluation (DOT&E), PEO IWS, ship class Program Offices, combat system element Project Offices, subject matter experts, and the Testbed engineers themselves.

The SECM provides a single, navigable documentation product utilizing visual and narrative descriptions of both 'what' and 'why' for the P_{RA} Testbed. Explanations of engineering judgments are inclusive to the documentation.

4. The Three Views of the SECM

The SECM is divided into 3 views, which generally follow sequential stages in Testbed system engineering:

- System View
- Model View
- Federate View.

Each view of the SECM is intended to reveal, address, and resolve a particular class of issues for P_{RA} Testbed accreditation (see Figure 2). By keeping issues cleanly divided and addressing each in depth the SECM provides an able documentation tool to support P_{RA} Testbed system engineering and accreditation for use in OT&E.

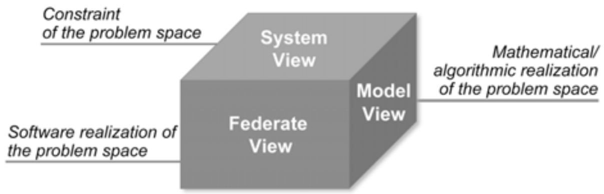

Figure 2. Systems Engineering Concept Model Views

4.1 System View

The System View of the SECM describes the real world systems and expresses the limit of understanding of the real world systems to be modeled. In practical terms, the System View provides the first insight into the scope of the problem space to be modeled. The System view explains what systems and platforms are to be included in the P_{RA} assessment, which aren't, and why. The System view explains the scenarios to be applied and what assumptions are included. This view provides a basis upon which to choose models to represent the required systems.

Example: The P_{RA} metric is expressed as a requirement for single-ship self defense capability against a given threat exposure. Definition of environmental conditions, indication and warning, and ownship/threat tactics are negotiated among the testers and ship class representatives. Results of these negotiations, of course, can have tremendous implications on simulation design decisions later in the system engineering process. The SECM captures the results of these negotiations, along with their rationale, in the System View.

Example: The LPD 17 sensor suite includes two primary active radars (SPQ-9B surface search radar, SPS-48E volume search radar), an electronic warfare receiver (SLQ-32), and other systems such as the SPS-73 navigational radar. For LPD 17 P_{RA} assessment the testers and ship class representatives agreed to include only the SPQ-9B, SPS-48E, and SLQ-32 systems in the LPD 17 performance assessment. Other systems such as the SPS-73 were disregarded. This decision, along with its rationale, is captured in the SECM System View. Further, resulting constraints on various system representation requirements are captured in this view, e.g., the sensor fusion system representation will not be required to include an SPS-73 interface.

The System View section of the SECM captures a number of results from negotiation between the testers and ship class representatives to establish boundaries of the P_{RA} assessment. In this regard, the System View informs, and is informed by the early objectives and requirements definition activities of FEDEP Step 1. As such, the SECM pushes conceptual modeling earlier in the FEDEP than formally called for in Step 2.

4.2 Model View

The Model View of the SECM describes the models to be used in the P_{RA} Testbed in mathematical and algorithmic terms. It describes equations, algorithms, and procedures to provide a basis for understanding the quality of system representations to be used in the Testbed. It provides insights into the strengths and limitations of the mathematical representations of the systems.

The Model View is concerned with the capabilities and limitations of the models to be used, but not their software realizations. The Model View is not concerned with functional allocation within the federation or eventual software implementation in federates. For example, the Model View will include descriptions of radar antenna models, signal propagation calculations, and target radar cross section models. Yet, explanation of whether each of these models is implemented in different federates or all in a single federate is left to the Federate View of the SECM. This can be particularly tricky, but also of utmost importance when addressing shared responsibilities (things multiple systems "touch") such as representation of threats and the natural environment. For the P_{RA} Testbed, the SECM treats the natural environment as a distinct, independent system to be modeled. This puts additional focus on the requirement to model the natural environment consistently across all systems in the P_{RA} problem space.

Example: The SLQ-32 electronic warfare system includes an operator in the loop. The P_{RA} Testbed LPD 17 baseline executes much slower than real-time, so for LPD 17 performance assessment the operator will not be a live individual. Rather, a mathematical model will be implemented that incorporates varying time delays to perform actions. The SECM Model View describes the mathematics used to represent the operator, explains the inherent limitations, and asserts a case for adequacy of the operator model. It discusses whether factors such as training levels, operational stress, and probability of correct decisions have been incorporated, and if so, how. The

Model View discussion of the SLQ-32 operator does not describe what software federate includes the operator model; that is for the Federate View.

Example: The SLQ-32 electronic warfare system includes a radio frequency receiver for detecting threat emissions. The Model View description of the SLQ 32 system representation includes a discussion of the SLQ-32 receiver subsystem model. The discussion includes the mathematical implementation of the receiver antenna and algorithms for signal detection. However, the Model View discussion of the SLQ-32 does not include a description of how threat emissions are modeled, though the same developer organization may be designing those equations and those calculations may ultimately be allocated with the SLQ-32 model into the same federate. Rather, the threat emission discussions are segregated to the threat modeling section of the SECM Model View. This isn't done to make life hard on the EW system modeler, but to enforce the discipline required to ensure the threat is represented consistently across the entire P_{RA} Testbed.

The Model View has been in many ways the most important yet most troublesome component of the SECM. Most simulation developers intrinsically jump from systems perspective to software perspective without much, if any, discussion of pure modeling. This has been particularly true when migrating legacy simulations to the P_{RA} Testbed. Requiring developers to think, and document, in federation-level terms segregated from their "home base" code has been an extremely challenging endeavor. Here the spiral nature of the FEDEP has been beneficial, as it permits multiple passes at the early system engineering steps as the spirals are executed.

4.3 Federate View

The Federate View of the SECM describes how the models have been broken up and clustered in the federation software (i.e., what went into what federates). This view provides insights into the strengths/limitations of the software realization of the models in the federation. This view distinctively reveals the implications of functional allocation within the Testbed. If, for example, a sensor model and target model are allocated to separate federates, the implications of requiring them to interact via the RTI are expressed in the Federate View. These include update rates, coasting or dead reckoning on data, and limits on data resolution. The Federate View also provides information on the Federation Agreements, Federation Object Model, and coordinate systems to be used in the Testbed federation.

Example: A primary self defense weapon on the LPD 17 is the Rolling Airframe Missile (RAM). During P_{RA} Testbed development, the threat airframe and RAM models were allocated to separate federates. Threat position and orientation updates are published to the RAM model across the RTI. Implications of this functional allocation decision on the RAM model are described in the SECM Federate View. An explanation is given for the minimum data rate to support model validity, as well as selection the dead reckoning algorithm chosen to compensate for target position data gaps.

The Federate View section of the SECM captures impacts of engineering judgments applied during functional allocation. In this regard, the Federate View informs, and is informed by the engineering activities of FEDEPS Steps 3-4. As such, the SECM continues explicit conceptual model development later in the FEDEP than formally called for in Step 2.

5. The SECM and the P_{RA} Testbed Systems Engineering Process

As previously stated, The SECM is an extension of the 'Conceptual Model' Product from Step 2 (Perform Conceptual Analysis) of the FEDEP. The SECM concept is an effort to broaden the conceptual model bounds in the FEDEP systems engineering process. The FEDEP is based on a spiral development process; the SECM ventures to capture the spiral maturation of a simulation from the objective and requirements statements through the functional allocation of federates.

Documentation for the SECM starts with the Step 1 of the FEDEP (Define Federation Objectives). In this step, the objective of the federation is stated which contains the overall plan for the simulation. It defines the purpose for the simulation, the system components necessary to conduct the simulation and what constraints are required from the Threats and Environment on the simulation.

For Step 2 of the FEDEP (Perform Conceptual Analysis), the SECM links the outputs from Step 1 with driven-down information needed for the Conceptual Model. In the Conceptual Model, the requirements listed in the Federation Objective are reviewed to create simulation scenarios. These scenarios must create the right test environment to answer the Federation Objectives. With scenarios decided upon, the next part of Step 2 is detailing the needs of each system component in the simulation. In the real-world systems, very complex physics, system interactions, and reactive behaviors are intrinsic to performance. To accurately depict these systems in the simulation world, the SECM endeavors to connect the real-world systems with the mathematical models that represent them. The requirements of the simulation are based on the real-world systems, which then translate simulation requirements for the models. Here the Model View of the SECM is paramount, and the requirement for disciplined system engineering is most stringent.

Once the Conceptual Model is drafted including the Federation Scenarios and the Federation Requirements, the SECM then connects the functions associated in the Conceptual Model with Step 3 of the FEDEP (Design Federation). To properly design the federation, the real-world systems turned mathematical models need to be accurately represented by their functions. Then the design and functional allocation can be drafted as a solution to answer the simulation objective.

With a drafted Federation Design in place, Step 4 of the FEDEP (Develop Federation) can begin. Because the FEDEP is a spiral development, the development of the federation will mature from 1…N builds resulting in integration and tests to properly assess the validity of the simulation. In this step, the SECM documents the Federation Object Model (FOM), which details the HLA objects used to represent entities and interactions; Federation Agreements, which details the rules of the federation and detailed Federation Scenarios including simulation standards.

The SECM is treated as a persistent document throughout P_{RA} Testbed system engineering. It captures at each step the important engineering decisions and forces the engineering documentation to not only describe "what" is modeled but also "why" it is good enough for OT&E. The intent of the SECM documentation process is to build into the system engineering the right artifacts to inherently support P_{RA} Testbed VV&A.

6. Lessons Learned

The original impetus for the P_{RA} Testbed SECM was simply to avoid glossing over the conceptual modeling task of early stage federation system engineering. It was understood that a top level "viewgraph" concept model would be insufficient rigor for the federation's intended use in OT&E. It was also understood that rigor applied early in the system engineering process would pay dividends in the VV&A process, though specific mechanics were not originally known. However, as the SECM development has progressed it has gained more persistent are far-reaching value. It has been used to:

- Document the "story" of the federation over a multi-year project with changing personnel
- Reveal more readily the implications of engineering judgments and programmatic decisions on the federation
- Provide a rubric for maturing federation capability across multiple complete federation development spirals.
- Provide the single, cohesive body of engineering documentation evidence for the VV&A case
- Establish a corporate knowledge base for subsequent ship classes in the T&E Enterprise.

Along the way a number of lessons have been learned, among them:

The SECM framework format is key. The division of system-model-federate views seems to make sense to a variety of constituents, including software developers, subject matter experts, military decision makers, and T&E professionals. The SECM documentation itself is built upon collected components that are organized in an HTML-navigable fashion. The ability to navigate non-linearly through information provides opportunities for different narrative threads for different readers and different purposes. This approach also tries to ease the burden on authors to produce large formal reports, leveraging bits of documentation wherever and whenever available. An unexpected benefit of this approach is it's well-aligned to spiral documentation, and readily absorbs maturing documentation alongside maturing federation capability. Though constituents are not always as forthcoming with specific documents as liked, they do understand and appreciate the 3-view structure and the associated documentation framework.

Decision makers both love and hate seeing consequences of decisions they make. The SECM is remorseless documentation, and it serves well as the conscience of the federation. This has been very important (particularly in the System View) for capturing results of compromises made by the testers or the ship class program office during development. It provides everyone a "receipt" that prevents re-treading technical ground already trod or re-hashing old decisions. This improves efficiency and provides a sense of security that results of decisions are firm and flow directly into federation development. However, negative consequences on federation capability are not obfuscated, which at times is irritating to the decision makers.

Engineers tend to think, and document, from a federate-centric vantage point. Participants in the federation development are most comfortable discussing their software. This federate-centric vantage point provides a home base for them, and it is an ongoing chore to segregate functions from federates. This is particularly tricky when wrestling with functions allocated from a single model into multiple federates. Convincing the engineers to embrace the premise of shared modeling responsibilities where the complete realization is allocated among multiple federates (e.g., threat representation) continues to be vexing.

Getting people to document "what it is" is very hard; getting them to document "why it's good enough" is even harder. Worse, many of the key pieces of validation evidence reside in the brains of people from whom obtaining thousands of lines of code is easier than tens of pages of report. In this regard, federation system engineering faces the same documentation problem as many technical projects. Yet, the requirement for federation accreditation heightens the demand for descriptions not just of "what" by "why" (e.g., not just how a radar antenna is modeled but why that's good enough for OT&E use). The necessity for written advocacy of a model (we have sometimes referred to this as "presenting your case to the jury") is fundamental to the V&V documentation package. This necessity has been slow to take hold with the P_{RA} Testbed developers. Fortunately, the Testbed spiral development process has provided multiple opportunities to redress this issue.

The SECM has been very effective at revealing inter-system gaps and assumptions. Here simulation interoperability is analogous to systems interoperability. The SECM takes a system-of-systems vantage point, and insists on enough detail to explain each element system and system interaction. Element system developers typically live in the world of their own system; drawing them out is challenging but necessary. The SECM was a very effective facilitator for creating that needed cross-talk. A factor contributing to its effectiveness was the persistence of the SECM throughout the development process. It wasn't perceived by the engineers as a "one and done" item of the SE process, but rather a key tool being maintained by the Federation System Engineer.

Much information exchange, especially at the working level, is not inherently documented. Yet, these decisions can have profound implications on federation performance and acceptability. This is particularly true when pairs or groups of engineers work out a compromise on a difficult problem. Often several assumptions get buried in the engineering negotiation, and don't show up in any formal documentation until goaded out.

A picture is worth a thousand spreadsheets. This is particularly true when a mix of constituents is involved; what makes intuitive sense to one group can be completely perplexing to another. Interoperable simulation inevitably causes federate developers to give up control of certain data or functions they are accustomed to controlling when running alone (e.g., the radar modelers were not accustomed to subscribing to reactive threat position data from an outside simulation). As obvious as it seems, the value of pictures over words or spreadsheets can't be overstated for facilitating effective communication. Graphical representation of FOM data captured in the SECM was specifically helpful.

The SECM done right automatically collects the core V&V documentation. Though it may be described as an overlay, VV&A is nevertheless intrinsic to the system engineering process. Accreditation for OT&E is a high hurdle to cross; it involves tough questioning from T&E professionals and requires significant evidence to prove worthiness. Yet, development of the SECM includes asking and answering those same tough questions. Further, the P_{RA} Testbed system engineering process included the T&E professionals as direct participants, such that any concerns or issues are echoed in the process artifacts. During LPD 17 P_{RA} Testbed development, the SECM – by answering questions and addressing concerns – became the natural repository for much of the engineering documentation needed to support the accreditation case. The real payoff for the Navy is the forward transition of this evidence to the other P_{RA} Testbed baselines in the T&E Enterprise: consistent system engineering documentation across ship classes used to maintain hard-earned confidence and minimize non-recurrent engineering costs.

7. Way Forward

The P_{RA} Testbed is a critical component of the U.S. Navy's Ship Self Defense T&E Enterprise; the Systems Engineering Concept Model is a critical component of P_{RA} Testbed systems engineering. The SECM pushes conceptual modeling both earlier and later than typically seen in the HLA FEDEP. It establishes a standing documentation tool that is well-suited to spiral development. The SECM provides a single, navigable documentation product utilizing visual and narrative descriptions of both 'what' and 'why' for the P_{RA} Testbed. Explanation of engineering judgments is inclusive to the documentation. As such, the SECM has become a key enabler of VV&A for the P_{RA} Testbed.

The SECM consists of both a process and a product. The process is the same for all applications but the product is specific to a particular application. The SECM itself captures the information in a series of diagrams and documents that exemplify various aspects of the particular application. Although the SECM artifact itself is specific to a given application, such as a P_{RA} Federation Testbed, much of the information captured will be reused in related applications. Such re-use will provide significant risk mitigation by promoting standardization and reducing non-recurrent engineering costs.

7. References

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Author Biographies

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