Blending the Real and the Virtual: An Experimental Framework for Co-Evolving Technology and CONOPs to Address Future Human Systems Requirements

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ABSTRACT

For more than 20 years, modeling & simulation, synthetic environments, virtual worlds, and gaming technology have been tools for wargaming and training. Beyond those traditional applications, there has been a trend to use such environments to assess design and mission performance. The future of human systems interaction will require an experimental framework that blends simulation and synthetic environments with real system-subsystems-components and/or models of these real world components. This will allow rapid and continuous design, development, testing and evolution of new human systems capabilities that will achieve mission metrics and provide a useful analytic focus on mission success in multiple domains. A notional view of this experimental framework is presented.

1.0 INTRODUCTION

Technology advancements—including sophisticated modeling and simulation environments and new abilities to analyze and model large, real world datasets—help explore new ways to evaluate and improve systems, missions and operations. Since the mid-1990s, a number of research and development teams have sought to explore the use of synthetic environments and virtual worlds. Beyond traditional approaches, including advancing and accelerating wargaming and training, the teams studied using such environments to explore new design spaces and trade-offs to improve the acquisition and operations processes. However, use of such environments for assessment has been limited to date due to scalability, robustness, completeness, and policy concerns.

While today's capabilities for assessing future mission effectiveness and system performance capabilities are limited, we can reduce these limitations by: (1) taking advantage of new computing capabilities, (2) focusing on jointly defining new experimental framework architectures that are open, flexible and affordable, (3) instituting processes that support both the co-evolution of technology and the concept of operations (CONOPs), and (4) developing an effective and systematic way of measuring mission effectiveness and system performance. Measuring mission effectiveness within a more robust, flexible modeling and simulation environment can provide a useful analytic focus that should improve the acquisition process.

Our vision is that the future of human systems interaction will require a new experimental framework, jointly designed by government, industry and academia, that blends simulation and synthetic environments with real system-subsystems-components and/or models of these real world components to rapidly and continuously design, develop, test and evolve new human systems capabilities that will achieve mission metrics. Our goal is to provide a forum for researchers, analysts, operations personnel, and technologists across academia, government, and industry to collaborate in a flexible 'sandbox' to develop evaluation experiments that employ realistic simulations and scenarios to test mission performance and efficiency of individuals and teams of operators.

This paper outlines the evolution of synthetic environments and addresses how emerging technologies and processes can foster a shared understanding of future environments and anticipate how people will interact in these environments.

2.0 BACKGROUND

2.1 Emergence of Synthetic Environments for Assessing Human Systems Design and Performance

While the use of modeling & simulation, synthetic environments, virtual worlds and gaming technology for wargaming and training has been emergent for more than two decades [1, 2, 3] there has also been a trend to use such environments to assess design and mission performance. Starting in the mid-1990s, a number of research programs explored using synthetic environments to assess and evaluate human systems design.

In 1997, Jones, et al. [4], sought to create models for acquisition and logistics processes and simulated their execution within a synthetic environment. They concluded that a “synthetic environment, can instrument and monitor an unfolding process and its constituent products to gather data for later analysis; or in real time, interactively ask ‘what-if’ questions by making adjustments to the products and processes to better understand resultant behavior.” Cooke and Shope [5, 6] described the use of synthetic task environments that provided a research platform to bridge a gap between controlled studies using artificial laboratory tasks and uncontrolled field studies on real tasks or using high-fidelity simulators. Their view was that simulations typically recreate a work environment and replicate equipment or systems within that environment, whereas synthetic task environments focus on the tasks and not necessarily on the precise view of the operational environment. They looked at the use of synthetic task environments to assess unmanned aerial vehicle (UAV) operator performance to determine the extent to which the environment is faithful to team cognition. They found that synthetic task environments can: (1) provide a rich test bed that permits experimental control, (2) facilitate measurement capabilities, and (3) be faithful to dimensions of the task. However, such environments without the experimental infrastructure are ineffective research tools and are more complex and expensive than traditional lab settings. Seymour, et al. [7] explored the use of synthetic environments to address C4ISR system development issues that more traditional methods could not solve. They believed the central role of the synthetic environment is to engage prototype systems and expert human users simultaneously with appropriate fidelity models of other component subsystems. The researchers found that in the initial phases of problem definition and system design, synthetic environments permitted system-of-systems evaluations with major components of human cognition and decision making, complex new technologies and many sub-system interactions, against metrics describing overall force effectiveness. The use of such environments however did not completely replace existing methodologies for system-of-systems (e.g., architectural framework approach, use of closed constructive simulation) due to lack of robustness to changing scenarios.

Mock [8] reviewed a number of synthetic environments and simulators established by various defense contractors and universities, ranging from self-contained environments to large distributed environments. That work sought to understand how these environments supported the CADMID (Concept-Assessment-Development-Manufacturing-InService-Disposal) process. Because a primary objective of human systems integration (HSI) is to reduce risk, and the introduction of new technology increases risk, they wanted to determine if synthetic environments could mitigate that risk by creating a forum for experimentation and testing. The researchers found synthetic environments tended to be used mainly during the concept and the assessment phases, while the manufacturing and disposal stages were relatively unsupported. Specifically, they found a range of HSI topics and methods were supported (e.g., investigations into human error, performance-shaping factors, system characteristics, training, display and control design, workload and team work) and that synthetic environments were considered to be potentially most supportive in information presentation and display design.

Vallerand and Thompson [9] explored a modular Modeling & Simulation/Synthetic Environment (M&S/SE) framework for developing and supporting a network-centric or distributed collaborative synthetic environments. The framework they designed depended on a layered, functionally separated approach to building dynamically reconfigurable applications. Each layer of the framework provided successive levels of specialization so that as new technology evolved, the implementation of the layer could be easily changed to accommodate new hardware/software or technology changes. They recommended that the general segmentation of a modular M&S/SE framework should include:

- Framework
- Simulation Runtime
- Software Development Environments
- Client Applications
- Server Applications
- Distributed HLA (High Level Architecture) Applications
- Management Application
- Common Synthetic Environment Infrastructure
- Dynamic Synthetic Environments/Computer Generated Forces.

They also determined that for such a framework to be implemented and used efficiently it required an open architecture concept. This allows modeling and simulation applications to be easily integrated onto a simulation platform from either the vendor, associated value-added partners or third parties. In addition, successful implementation requires systematic rules for integration. An ad-hoc mixture of interconnected services and components usually fails to work and the successful adoption of a network-centric distributed collaborative synthetic environment might involve significant changes in how large organizations (e.g., defense departments, healthcare organizations, etc.) actually organize themselves.

In 2005, Harmer [10] produced a thorough review of existing synthetic environments and software tools and involved a wide range of stakeholders across government and industry entities. This review had different conclusions about the promise of using synthetic environments and gaming technology for the purpose of assessing design and human system performance. The stakeholders observed that the use of synthetic environments and gaming technology for design evaluation was not adequately justified:

- There is no strong consensus on the synthetic environment related research priorities and some research may be duplicated.
- While there is general interest in the potential benefits offered by the use of modifiable games technologies, there is also concern that benefits are being ‘over-rated’ and barriers to exploitation have yet to be fully explored.
- There appears to be little support for proposed research into the development of guidelines for the use of synthetic environment to improve the human systems design process.
- There are financial, organizational and cultural barriers that restrict the potential for synthetic environment re-use.
- Industry stakeholders want to better understand the role of, and interfaces between, the various skills and disciplines required to develop synthetic environment architectures and experimental processes.
- Industry has invested in significant synthetic environment capabilities and desires to exploit re-use across projects and across the lifecycle, but re-use to date has been limited and expensive, concentrated on the early concept, assessment and demonstration phases.

These observations imply that policy and investment strategies need to be examined.

2.2 Beginning of the Blending the Real and the Virtual

Despite the barriers identified in the mid-2000s, research continued on, fueled by increasing life-cycle costs of large complex systems. Srivastava et al. [11] re-expressed the notion that computer-based simulations are an effective tool for human system integration optimization, as well as for studying the risks associated with complex interaction between crew and systems, leading to potential reduction in life-cycle costs. Their modular simulation environment empowered analysts to choose and integrate the best combination of agent, discrete event, and physics based simulations to address questions of shipboard staffing.

They concluded that while a number of systems engineering tools existed to support ‘what if’ trade studies (e.g., manual and parametric estimation approaches for affordability, engineering ‘build-up’ tools, behavioral rules, etc.), a synthetic environment can be used to estimate the relationship between a technology and shipboard staffing and that simulations can address the risks associated with the complex interactions of personnel and systems of systems since the human element that produces surprises in unforeseen situations.

Miedema et al. [12] reinforced this view, but pushed the notion that the value of synthetic environments was as a collaboration tool. They maintained that supporting the early design stages with a method that integrates the available aids and allows stakeholders to experience the consequences of the design decisions they take and since in the early design stages a prototype of the product is not yet available, the communication among the various stakeholders is typically inefficient or even absent. They used a synthetic environment in a case study with industrial partners that revealed that a low-cost, easily accessible setup, consisting of haptic and visual simulation only, was sufficient for a realistic evaluation of a product and to provide meaningful information to improve its design.

In 2007, Bengtsson et al. [13] through the SIMBASE project, sought to deliver a practical demonstration of synthetic environment-based acquisition through maintaining: (1) a coherent and consistent approach to the acquisition process, (2) an effective and efficient systems engineering process, (3) software interoperability through open standards, and (4) use of modeling and simulation to support the entire process. Using a submarine rescue craft as the product under design, the SIMBASE crew built and executed a synthetic environment architecture with workflows that permitted: (1) systems engineers to develop functional models, (2) synthetic environment engineers to identify required characteristics against elements in the functional model, (3) logistics engineers to perform analyses to provide values for required characteristics, and (4) synthetic environment engineers to use these values to execute the simulation.

At the same time, in addition to the acquisition-based arguments for continuing investigation of synthetic environments, Jenkins et al. [14] restated the need for such environments to improve training and operational readiness. Since military environments are typically prone to unexpected and unanticipated events, it is almost impossible for information-based training to equip decision makers with appropriate stored-procedures that will allow them to cope with these situations. They contended that by optimizing the design of synthetic environments, expertise acquisition can be expedited and the characteristics of synthetic environments can clearly offer the potential to allow experience to be gained in compressed time periods while subject to experimental control.

Over the past few years, the trend for using synthetic environments to build smarter evaluation testbeds has continued to evolve. In the early 2000s only the first portions of the CADMID cycle were addressed, but government and industry partners began to expand synthetic environments to accommodate the entire process across the Live-Virtual-Constructive spectrum. Goddard [15] described the blending of synthetic environments with real systems-under-test, also known as a ‘through-life testbed,’ on a recent complex weapon development program. Essentially, Goddard and his engineering team followed a process, which allowed the synthetic environment to evolve to supports higher fidelity components and to promote smart prototyping and integration. Generic testbed architecture was adapted to suit the specific weapon system, following the architecture of the complex weapon system. This testbed then supported a number of concept studies, experimentation and development of the system CONOPs, system design alternatives, human systems integration points, interoperability, system 'proving,' and training aspects. The team also demonstrated the sharing and reuse of these capabilities across projects.

As synthetic environments were beginning to become more expansive across the system lifecycle, the need to establish a broader, more universal approach to system design, training, and mission operations was emerging. Tangney [16] introduced the concept that not only were synthetic environments needed to accelerate and improve the acquisition process (e.g., explore the human systems design space, assess risk earlier) and training (e.g., more realism, in-line assessment, distributed), but that evaluation needed to be performed in the context of achieving mission operation metrics (e.g., readiness, adaptive planning, flexible force). He indicated that successful use of synthetic environments would first require the building of a 'laboratory version' of a real-world naval task where the synthetic environment would support simulation in form but that fidelity could be traded for flexible experimental use. The goal would be to: (1) build multiple task scenarios within the environment, seeking functional equivalence to operational tasks, (2) attach naval mission effectiveness metrics scenarios and allow hooks for discipline-specific scientific measures, (3) calibrate metrics using naval operators, and (4) distri-bute to broad science and technology community to gain estimates of technology contributions in naval terms.

2.3 Blending the Real and the Virtual: Tying Together Synthetic Environments for Assessment and Engineered Resilient Systems (ERS)

In the previous sections we discussed the use of modeling & simulation and synthetic environments to improve the acquisition process, training and operations readiness. This perspective was notably focused on HSI factors and the impact on human systems design and performance. There has been a parallel activity focused on enhancing engineering productivity through 'engineered resilient systems.'

With the advent of increased computational power and availability, there is now more flexibility in data exploitation and application of services. Using this new capability, the ERS concept envisions an ecosystem in which a wide range of stakeholders continually cross-feed multiple types of data that inform each other's activities.

Neches [17] and Baldwin [18] are exploring the notion of dramatically boosting engineering productivity, sufficiently enhanced to enable rigorous analysis of alternatives and refinement of requirements. As with the use of synthetic environments to explore the design space, the thrust for engineered resilient systems (ERS) seeks to concurrently explore system concepts, operational concepts, and engineering issues and to make it affordable to do rigorous "up-front engineering." Specifically, they are looking to quantify the difference that three key ERS concepts might make to: (1) understand consequences before making trade decisions and (2) explore more options and keep options open longer:

- Flexible workflow enabling engineering and operational considerations to jointly manage exploring large tradespaces.
- Tradespace analysis tools enabling requirements refinement informed by rigor.
- Cross-Domain coupling enabling combined models that reveal interacting factors.

They want to produce a shared conceptual framework and architecture for ERS that will help align and harmonize future government activities: (1) provide a 'big picture' and architectural structure to inform systems and platforms thinking, (2) create an example joint testing environment, and (3) develop a sample engineering test set for future experiments. The ERS concept looks at building robust systems with broad utility, in a wide range of joint operations, and across many potential alternative futures. Current areas of interest include:

- Systems Representation and Modeling
  - Physical, logical structure, behavior, interactions, interoperability
- Characterizing Changing Operational Contexts
  - Deep understanding of warfighter needs, impacts of alternative designs
- Cross-Domain Coupling
  - Model interchange & composition across scales, disciplines
- Data-driven Tradespace Exploration and Analysis
  - Multi-dimensional generation/evaluation of alternative designs
- Collaborative Design and Decision Support
  - Enabling well-informed, low-overhead discussion, analysis, and assessment among engineers and decision-makers

3.0 A NEW EXPERIMENTAL FRAMEWORK TO CO-EVOLVE TECHNOLOGY AND CONOPS

Based on the history of using synthetic environments for assessment, the emergence of engineered resilient systems concepts, and the evolution of more powerful computing capabilities and architectures, we contend that a new experimental framework should be jointly designed and developed by government, industry and academia to realize the aforementioned goals of creating better human systems design and performance requirements across multiple domains (e.g., defense, healthcare). This new framework will require: (1) adherence to a rigorous experimental methodology and process and (2) designing and building a robust environment to execute new system design experiments.

3.1 The Experimental Process: Co-evolving Technology and the Concept of Operations to Build Human Systems Requirements

System Level Experimentation, identified by Cross and Fouse [19], is an approach to flexible exploration of alternative system concepts and system-level discovery experiments focused on disruptive ideas in future environments to aid in earlier discovery of game-changing ways to fly and fight. Their approach supports discovery-level experiments by both developers and test & evaluation engineers. Weiss et al. [20] further elaborated on this concept and identified a strong need to conduct systems engineering testing for coupled exploration of technologies, concepts of operations (CONOPS), and capabilities all driven by increased connectivity, increased capabilities, and operations in complex adaptive environments.

The basic approach identified by the researchers above, and termed the Co-evolution Experimentation (COVE) process here (see Figure 1), requires two basic attributes:

1. Co-evolution of Technology and CONOPS: Concepts for new capabilities and technologies are introduced in support of a new CONOPS. These concepts can be tested across wide range of representative and realistic operational environments, both live and virtual, while stressing evaluation of unprecedented, innovative, and interacting systems operating in unpredictable environments.
2. Experimentation: Executing a series of experiments that engage both developers and evaluators to explore system alternatives results in early discovery of both good and bad design attributes is required. Part of this process is to evaluate concepts in situ by end users, with ”after action” workshops, that encourage end users and technologists to collaborate and to shape and steer development toward high-value capabilities.

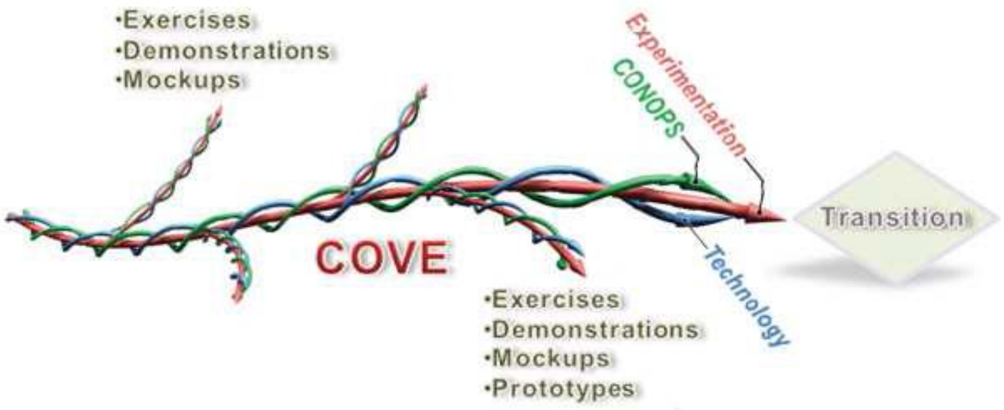

Figure 1: Co-evolution Experimentation (COVE) Process

In summary, the co-evolution of technology and CONOPS can be significantly accelerated through a series of experiments and exercises. Application of this or a similar process is paramount to accelerating the assessment of human systems design in conjunction with the experimental framework based on synthetic environments.

3.2 Recommendations for Designing a New Experimental Framework

Based on the evolution of synthetic environments and the emergence of the engineered resilient systems concept, a new experimental framework needs to be jointly developed with government, industry and university partners. This framework would blend the capabilities of synthetic environments for assessment, emerging capabilities from engineered resilient systems and new computing capabilities to enable exploration of large design spaces.

First, in addition to adhering to an experimentation process, such as the COVE process described above, supporting well-defined effectiveness and performance metrics will be needed to explore trade space analyses within a mission. Jensen and Tangney [21] addressed the nature of needed effectiveness metrics: (1) realistic mission training simulations that are 'lightweight,' (2) mission success metrics, (3) calibration of metrics using experts in the loop, and (4) integration from a Joint, Coalition perspective. In addition to metrics definition, there may be an opportunity to also explore simulation as a significant method for theory development. Davis et al. [22] observed that as organizations and strategists increase emphasis on 'theory explaining dynamic and longitudinal phenomena,' new simulation frameworks and methods with the ability to quickly create computational representations, perform experiments and validate results with empirical data might be useful in theory creation.

Second, we need to characterize gaps and identify potential solutions. Kettler [23] has identified a number of gaps with current simulation environments:

- Current simulation environments lack the ability to continually perform desired analyses rapidly and affordably on the most current data throughput the design process and product life-cycles.
- Current virtual worlds and synthetic environments are too heavyweight and inflexible.
- Robust, explicit modeling of the human element (individuals, teams, organizations, etc.) is needed.

These limitations might be overcome by providing:

- Open, meta-model frameworks that provide high-level simulation architecture, including exploiting libraries of reusable, composable models.

- Blended environments that accommodate Platform Scalability, Distribution, Security, Open Source, Defining and Utilizing Standards, Future Proofing, and accommodating stakeholder Business Models.
- Open model repositories for model sharing, using the frameworks to rapidly exploit existing models, rapidly configuration of models, and validating and running models on dynamic data from open media.

Third, we need to redefine a new architectural view that takes advantage of new high performance computing, cloud computing technologies, and massive data analytics capabilities. To deeply explore future design concepts and future mission scenarios that carry many uncertainties (e.g., anti-access area denial), ‘shared situational knowledge’ will provide the foundation for new and different capabilities. While a co-evolution experimentation process provides the recipe for capturing experience, context, training and judgment as part of this new experimental framework, we must accommodate the ability to model and simulate the events and phenomena needed for robust, dynamic and distributed experiments. In reviewing emerging capabilities for defense experimentation, Macedonia [24] identified the challenges with legacy simulation systems (e.g., heavyweight hardware, dedicated computer networks, tightly integrated software, relevancy, etc.), but indicated that ‘exploiting virtual worlds’ technology is fundamental to developing cutting edge defense capabilities for future threats. He identified a number of items that need to be addressed for the next generation simulation environments: connection to the real world, core infrastructure (i.e., high performance computing, cloud computing, ‘simulation as a service’) for future virtual world development, robust analytical tools, ubiquitous interfaces to a wide variety of information appliances and other real systems, and scalability. Some of these items are being addressed as some large simulation systems, like OneSAF, continue to evolve, but we believe that to overcome most of the current limitations delineated above, the new experimental framework needs to be jointly designed by government, industry and academia in a standardized fashion.

As depicted in Figure 2, Damiano [25] has identified a notional high-level functional architecture for a new synthetic environment for assessment (SEA) experimental framework, which might address many of the limitations outlined above.

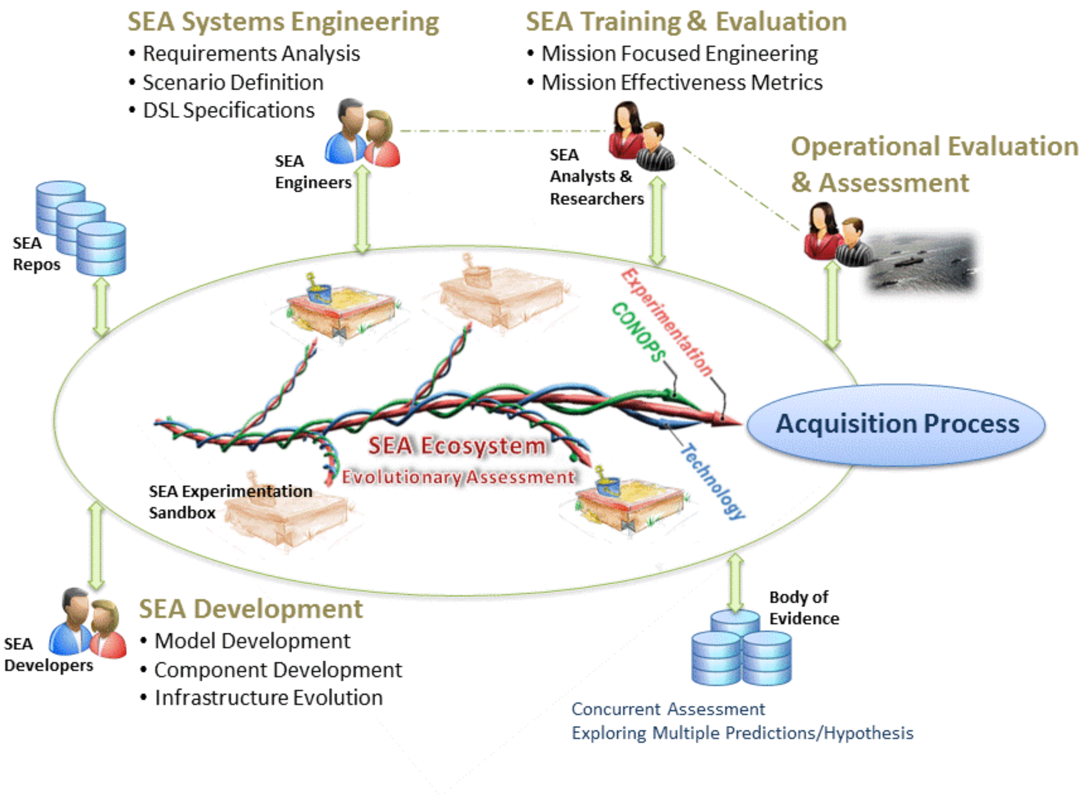

Figure 2: Functional View of a Synthetic Environment for Assessment Experimental Framework

The basic infrastructure would support concurrent testbeds and distributed operations and would include:

1. Scalable Testbed Environment that seamlessly combines Virtual Machines intermixed with physical machines to meet fidelity and scaling requirements:
   - Portable, small scale SEA deployments in fully virtualized testbed nodes
   - Medium Scale (desktop) and Large Scale (data center) deployments for higher fidelity requirements
   - Dynamically Configurable Infrastructure that manages the simulation network and computing cluster
2. SEA Domain Specific Language (DSL) environment to reduce brittleness and hardwiring. The DSL would describe (through recipes) domain specific testbeds, including items such as hardware and networking, and component & model configuration. The DSL would leverage emerging standards (e.g., MSDL, SDL, BOM, RPR, SEDRIS).
3. SEA Network Stack that provides a network emulation framework that includes flexible link and network conditioning.
   - Pluggable Communication impairment models/packages (e.g., RF models, QoS, MAC algorithms).
   - Distributed Communications and external systems interoperability.
   - Network Management & Virtualization (Layer-1 and Routing).

The Runtime and Development Environment would support:

4. SEA Toolkit for defining training scenarios, tests, requirements, constraints, system capabilities, etc.
   - Editing and Manipulation of SEA DSL.
   - Training Scenario Development.
   - Managing Training Progress and Material.
   - Support development of SEA compliant components and models.
   - Runtime binding of recipes onto SEA components and models.
5. Model and Component Orchestration support via SEA DSL recipes and the runtime infrastructure.

3.4 Emerging Experimental Framework Examples

Lockheed Martin (Boon [26]) is currently deploying a distributed testbed, focused on Integrated Air and Missile Defense (IAMD) for conducting cross-cutting mission analysis, demonstrations, mission planning, and training to evaluate regional capabilities, CONOPS, communications needs, and interoperability with partners in a collaborative environment. The IAMD Testbed provides and addresses complex, mission-level analysis and the warfighting environment and the performance of the sensors, and command and control.

The IAMD Testbed is “connect anywhere” distributed, cloud-based, simulation environment via a secure, high speed VPN. This environment is ideal for computational “heavy lifting” and all possible actively participating simulations are run within the cloud. The IAMD Testbed supports

- Exportable simulations
- Exploration of interoperability concepts
- Exploration of regional and global considerations of coalition IAMD
- Operator-in-the-Loop interfaces
- Perceived and truth scenario visualization
- Data collection for real-time and offline analysis and replay

In another example, Lockheed Martin (Hannon [27]) has developed a design space capability, Tools for Integrated Model-Based Representation (TIMBR), which integrates system engineering and analysis capabilities to provide a framework for expanding system definition based upon analysis results. TIMBR includes three basic components to execute new platform designs based on flexible user input parameters: the system architecture model, system analysis models, and component analysis models. For example, TIMBR was used to build a conceptual automated UUV (Unmanned Underwater Vehicle) sizing environment to permit designers to rapid vary a number of UUV characteristics (e.g., propulsion, energy—batteries/engine/fuel cells, floatation, subsystems—thrusters/electronics, reliability, cost) resulting in a brand new simulated platforms.

Although the IAMD Testbed and TIMBR do not contain all of the characteristics identified for the new experimental framework, they are representative examples of the merging of synthetic environments, physical system modeling tools with new computing technologies working in a distributed fashion. Further, although these examples focus on military operations, the same technology base can be applied to other domains (e.g., healthcare).

4.0 CONCLUSIONS

Based on the history of using synthetic environments for assessment, the emergence of engineered resilient systems concepts, and the evolution of more powerful computing capabilities and architectures, a new experimental framework should be designed and developed to realize the aforementioned goals of creating better human systems design and performance requirements across multiple domains (e.g., military operations, healthcare). This new framework will require: (1) adherence to a rigorous experimental methodology and process and (2) designing and building a robust environment that takes advantage of new high performance computing, cloud computing technologies, and massive data analytics capabilities to execute new system design experiments. The new framework should be jointly designed by government, industry and academia to overcome technology and policy challenges.

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