

Advanced Modeling and Simulation Techniques for Evaluating System-of-Systems Performance

Robert Lutz
The Johns Hopkins University
Applied Physics Laboratory
Laurel, MD
Robert.lutz@jhuapl.edu

Thomas Hanrahan
Naval Air Systems Command
Patuxent River, MD
Thomas.hanrahan@navy.mil

Dan Schneider
AMEWAS, Inc.
California, MD
Danschneider@amewas.com

Matthew Edwards
MIT Lincoln Laboratory
Lexington, MA
Matthew.edwards@ll.mit.edu

Rick Graeff
AFLCMC/XZS
WPAFB, OH
Richard.graeff@wpafb.af.mil

Nancy Gould
Naval Air Systems Command
Patuxent River, MD
Nancy.gould@navy.mil

ABSTRACT

Engineering a System-of-Systems (SoS) solution for complex military problems introduces special challenges. While system engineering processes for the design and development of individual systems are relatively well-defined in DoD policy directives, engineering processes for a SoS solution are less mature and less tractable due to the reliance on existing system components developed according to a disparate set of requirements, that serve different users, and which were never designed to interact with other systems in a SoS context. Still, the realities of constrained budgets and the inherent complexity of modern operational strategies and tactics requires the seamless integration of multiple sensor, weapon, and communication systems to achieve the desired military capability of net-centric warfare in a joint operating environment.

The Navy's Triton Program (MQ-4C) is developing a high altitude, long endurance Unmanned Aircraft System that is required to operate safely and effectively in the vicinity of other air traffic. Triton depends on a layered defense strategy involving seamless interoperation of multiple Sense and Avoid (SAA) system elements as part of a larger Concept of Employment for strategic separation and collision avoidance. To verify that potential hazards in the Triton operational environment can be effectively mitigated, the Triton Program relies heavily on Modeling and Simulation (M&S) to generate evidence substantiating safety claims related to SoS performance. This paper focuses on the application of advanced M&S tools and techniques to support the Triton Safety Case. Special considerations for modeling overall SoS performance and behavior will be discussed, including issues related to the characterization of complex airspaces, runtime interaction among disparate system models, the role and relationship of constructive and virtual models in SoS analyses, the buildup from simulation to emulation to hardware-in-the-loop (HWIL) M&S, and VV&A of SoS representations.

ABOUT THE AUTHORS

Robert Lutz is a principal staff scientist at The Johns Hopkins University Applied Physics Laboratory in Laurel MD. His background includes 32 years of practical experience in the development, use, and management of models and simulations across all phases of the DoD systems acquisition process. He currently serves as the Airspace Integration M&S lead for the Navy's Triton Program and supports the Modeling and Simulation Coordination Office (MSCO) through a variety of technology development programs and standards development initiatives. Mr. Lutz also serves as the Chair of the Simulation Interoperability Standards Organization (SISO) Executive Committee, serves on the Tutorial Board and Fellows Committee at the Interservice/Industry Training, Simulation and Education Conference (IITSEC), and is a guest lecturer on M&S-related topics in The Johns Hopkins University Whiting School of Engineering.

Thomas Hanrahan is a senior engineer with the NAVAIR Warfare Center Aircraft Division (NAWCAD) at Patuxent River, MD. He has worked primarily in avionics and weapon systems over the past 31 years. He was a prime developer and patent holder of the Terrain Awareness Warning System (TAWS) software that has been integrated on multiple Navy aircraft, leading to a drastic reduction in loss of aircraft due to Controlled Flight into Terrain (CFIT). Mr. Hanrahan currently works for PMA262 as the Sense and Avoid (SAA) lead for NAVAIR unmanned aircraft.

Dr. Dan Schneider is Chief Engineer for American Electronic Warfare Associates (AMEWAS) in California MD. His experience includes 23 years as an Air Force pilot and he is a combat veteran of the Gulf War. A graduate of both Navy Test Pilot School and the Navy War College, Dan holds an Airline Transport Pilot License (ATP) having also retired after 18 years as a Captain from American Airlines where he flew B727, MD80, B757/767, and the B777. During his tenure at Patuxent NAS, he was the head of the Aircrew Systems Test and Evaluation Facility and lead test engineer for controls/displays for numerous Navy aircraft during the mid-80s, having developed methods for conducting automated testing of communications systems, workload analysis via simulation and Operations Research associated with both fixed and rotary wing aircraft. Dr. Schneider has presented at AIAA and HUMFAC Association conferences. He received his MS from University of Southern California and his Ph.D. from George Washington University Schools of Engineering and Applied Sciences.

Matthew Edwards is a member of the technical staff at MIT Lincoln Laboratory in the Air Traffic Control mission area. His research interests include control and estimation, optimization, and the modeling and assessment of complex aerospace systems. At Lincoln Laboratory, his work spans the assessment and technology development of collision avoidance systems for manned and unmanned aircraft. He holds B.S. and M.S. degrees in Aerospace Engineering Sciences from the University of Colorado at Boulder.

Rick Graeff is the Infrastructure Branch Chief at the Simulation & Analysis Facility, Simulation & Analysis Division (AFLCMC/XZS), Program Development and Integration Directorate, WPAFB, OH. Richard has been the Tech Lead for UAS Projects @ SIMAF for over 13 years, and has been involved with UAS Airspace Integration for 6 years, currently leading the Air Force Airborne Sense & Avoid Program M&S IPT and overseeing several studies for the OSD UAS Airspace Integration IPT, Navy Triton, and Air Force Global Hawk Programs.

Nancy Gould holds a BS in chemical engineering from the University of Michigan, an M.S. in Applied Statistics from The Ohio State University, and an M.A. in National Security and Strategic Studies from the Naval War College. Ms. Gould has extensive experience in modeling, simulation, and analysis as well as VV&A. She is currently employed by the Battlespace Modeling V&V Branch at the Naval Air Systems Command (NAVAIR) in Patuxent River, Md. and provides VV&A support to various acquisition programs including Triton UAS.

Advanced Modeling and Simulation Techniques for Evaluating System-of-Systems Performance

Robert Lutz
The Johns Hopkins University
Applied Physics Laboratory
Laurel, MD
Robert.lutz@jhupl.edu

Thomas Hanrahan
Naval Air Systems Command
Patuxent River, MD
Thomas.hanrahan@navy.mil

Dan Schneider
AMEWAS, Inc.
California, MD
Danschneider@amewas.com

Matthew Edwards
MIT Lincoln Laboratory
Lexington, MA
Matthew.edwards@ll.mit.edu

Rick Graeff
AFLCMC/XZS
WPAFB, OH
Richard.Graeff@wpafb.af.mil

Nancy Gould
Naval Air Systems Command
Patuxent River, MD
Nancy.gould@navy.mil

BACKGROUND

Good systems engineering (SE) practices are critical to containing costs and ensuring a high level of technical quality for systems acquired by the U.S. military. The term “systems engineering” has been defined in different ways across the broad spectrum of supporting literature resources available to systems engineers, but they all represent a variant of the following definition from the Defense Acquisition University (DAU):

Systems Engineering is an interdisciplinary engineering management process that evolves and verifies an integrated, life-cycle balanced set of system solutions that satisfy customer needs (“Systems Engineering Fundamentals”, 2001)

The Office of the Deputy Assistant Secretary of Defense for Systems Engineering [ODASD(SE)] is the focal point for all policy, practice, and procedural matters relating to Department of Defense (DoD) systems engineering. The OSASD(SE) website (<http://www.acq.osd.mil/se/>) provides links to a wide range of SE resources, including such well-established, mature SE process standards as ISO-IEC 15288 (Systems and Software Engineering -- System Life Cycle Processes) and ISO/IEC 2670 (Systems Engineering -- Application and Management of the Systems Engineering Process). The International Council on Systems Engineering (INCOSE) has a working group that is also focused on SE standards, which includes both process standards and standards for supporting process enablers such as Systems Modeling Language (SysML).

As modern military operational strategies respond to the increasingly complex and unpredictable tactics of asymmetric threats, there is an emerging but immediate need for individual military systems to quickly and seamlessly interface with other military systems in order to collectively create new synergistic capabilities. The assemblage of component systems is what is referred to as a “System of Systems” (SoS). The Joint Capabilities Integration and Development System (JCIDS) defines a SoS as “a set or arrangement of interdependent systems that are related or connected to provide a given capability, where the loss of any part of the system will significantly degrade the performance or capabilities of the whole” (“Joint Capabilities Integration & Development System”, 2005, p. GL-15).

SoS development frequently requires the integration of component systems that were developed according to a disparate set of requirements, that serve different users, and which were never designed to interact with other systems. Thus, from a system engineering perspective, SoS development introduces many new challenges, including the fact that processes and tools for SoS development are relatively immature. Still, progress is being made. For instance, a workshop was hosted by the Carnegie Mellon Software Engineering Institute (SEI) in 2006 to identify and resolve issues related to SoS requirements management (“Requirements Management in a System-of-Systems Context: A Workshop”, 2006). Based on initiatives like this, efforts to modify existing SE processes to account for SoS concerns are ongoing with some notable successes (Dahmann, Lane, Rebovich, & Baldwin, 2008). In addition, the Office of the Deputy Under Secretary of Defense for Acquisition and Technology [ODUSD(A&T)] Systems and Software Engineering published a *Systems Engineering Guide for System of Systems* in August 2008

(see Reference 5). This guide identifies the many core process elements associated with systems acquisition and tailors the existing systems engineering principles for use within a SoS context.

As the body of knowledge for best SoS engineering practices continues to evolve and expand through organizations such as the National Defense Industrial Association (NDIA) SoS Engineering Committee, the tools and other enablers that support these best practices must also evolve. Modeling and Simulation (M&S) is an especially critical SE enabler, as all modern DoD acquisition programs leverage M&S to varying extents across all phases of the product lifecycle phases. However, like the SE processes they support, current M&S best practices are generally focused on engineering individual systems. Identifying how these practices can be modified and/or extended to address the special challenges associated with SoS engineering is not immediately obvious.

M&S CHALLENGES

M&S supports acquisition in a variety of different ways, depending on the SE process phase. Early in an acquisition program, M&S is used to explore current system capabilities versus existing and projected threats for requirements development purposes. It is also used to determine relative utility of different system options as part of concept exploration. In the middle phases of the SE process, M&S is employed to downselect among multiple competing system designs and for optimization of the chosen design prior to initial production. Later in the SE process, M&S is used to maximize the efficiency of manufacturing processes, to support system test and verification, and for system training (Piplani, Mercer, & Roop, 1994). M&S is thus crucial to the conduct of most SE tasks, as acquisition stakeholders could not perform their assigned tasks without it.

While there are still many difficult issues related to the use of M&S in support of acquisition functions, the sheer complexity of most practical SoS applications introduces some new and very difficult challenges for the M&S needed to support SoS development. The focus of this paper is on the following areas:

Management of Multiple Processes: A SoS is, by definition, a complex system with many diverse component systems interacting cooperatively in order to create the broader capability desired by the end user. M&S tools for SoS development need to be able to represent the entire SoS at the user-specified level of fidelity and also replicate the complexities of the operational environment in which the SoS must reside. Rather than address this broad set of requirements in a single monolithic model, SoS representation generally requires a family or federation of models to capture all aspects of the SoS and operational environment relevant to the intended use. While simulation architectures and supporting technologies exist to support runtime integration of live, virtual, and constructive (LVC) simulation assets, managing the construction of a suitable LVC environment for properly engineering a SoS requires a higher degree of project control than for similar environments used for assessment of individual systems. Like the SoS components themselves, the models and simulations representing the individual systems that comprise the SoS are likely to be owned by different organizations, developed using a diverse and possibly incompatible set of interfaces/data formats, and inconsistent in terms of the semantic content of the data the models need to exchange to represent the full SoS. The process of how to integrate the various M&S components (either serially or at runtime) into a larger M&S system capable of accurately representing the SoS requires a more formal, structured, and controlled development process to successfully adjudicate the many technical and programmatic issues that arise across the diverse set of stakeholders in this process.

Mixed Fidelity: The range of stakeholders that can benefit from a simulated representation of a SoS cuts across many disciplines, such as analysis, T&E, and training. Since those users have different interests, it is reasonable to expect that they may also have different M&S fidelity requirements. However, even within a single user class, the fidelity requirements of different parts of the SoS representation may vary. For instance, a user may want to assess the relative contribution of one component system to overall SoS performance, and thus needs high fidelity for that component. Depending on the intended use, that user may not require the same level of fidelity for other SoS components, and in fact may not be able to achieve the same level of fidelity across the entire SoS representation (or for other entities in the operational environment) due to computational or network bandwidth limitations. Given the limitations of the underlying M&S infrastructure, the challenge is how to achieve effective and (relatively) seamless interoperability among dissimilar M&S components at different levels of fidelity as needed to effectively capture SoS performance in complex operating environments.

Human Behavior: Many types of issues related to SoS performance can be addressed effectively through constructive M&S. Constructive M&S can be used to evaluate a very wide tradespace of system and SoS options very quickly and efficiently. Also, stochastic factors can be accounted for in constructive model and simulations via

Monte Carlo methods, using random number streams to determine stochastic events and gathering statistically significant results over a large number of runs. However, the credibility of constructive M&S results normally has at least some dependence on how accurately human performance and behaviors are modeled. Techniques for modeling human behavior have advanced in recent years, but the ability to simulate humans in constructive M&S tools depends very much on the complexities of the systems the simulated humans either operate or encounter, the complexity of the operational environment the simulated humans interact with, and the types and frequency of the decisions that the simulated humans make during the simulation. For SoS assessments, these factors strongly influence simulation results, and thus inserting actual humans into the M&S infrastructure is frequently a requirement to achieve the desired level of fidelity for human representation. But this implies real-time only, which introduces a wide range of limitations in terms of the breadth of the SoS design options that can be investigated and the range of operational conditions that can be considered. The challenge in this case is how to properly integrate real-time live/virtual simulations with faster-than-real-time constructive simulations to produce statistically significant results for the SoS in question while assuring a representation of human performance consistent with the intended use.

Verification, Validation, and Accreditation (VV&A): VV&A policy directives for M&S VV&A are pervasive throughout the U.S. military, and techniques to generate V&V data are openly available to M&S users (see <http://vva.mscs.mil/> for *DoD M&S VV&A Recommended Practices Guide [RPG]*). This guidance spans both standalone and distributed M&S and is very relevant to how a SoS M&S representation may be evaluated for credibility. However, the number and diversity of the organizations that own the various M&S components of the SoS representation can make it difficult to collect V&V data on the individual M&S components, as what data is provided may have varying formats and content (if it exists at all). This may make it difficult to develop a clear picture of where the relative risk across the full M&S system lies. In addition, since a simulated SoS is likely to function much like the real SoS (through defined interfaces), extensive V&V testing may be required to ensure the M&S components interoperate as a unified whole and collectively provide a realistic representation of SoS performance. This implies a structured, formal VV&A process with a potentially intensive V&V data generation activity and a knowledgeable Subject Matter Expert (SME) team being available to properly assess the V&V data. All of these elements must be present to build a complete, robust case for accreditation of the SoS representation within the context of the intended use, but this need frequently exceeds program resources for SoS assessments.

In summary, there are many barriers to building a credible SoS representation in M&S and exercising that representation in defined operational conditions. However, there is no real alternative to M&S for SoS assessments. The sheer complexity of these representations effectively rule out most analytical methods, and live SoS testing may not be practical due to the costs of fully replicating the SoS and operational environment on a test range as well as possible safety restrictions for some test configurations. Thus, solutions to the stated issues will be critically important in the future as SoS assessments become more prevalent and frequent across the DoD.

TRITON AIRSPACE INTEGRATION – A SOS CASE STUDY

The MQ-4C Triton is a high-altitude, long-endurance unmanned aircraft system (UAS) suitable for conducting continuous sustained operations over an area of interest at long ranges. It relays maritime intelligence, surveillance and reconnaissance (ISR) information directly to the maritime commander. Triton is capable of providing persistent maritime surveillance and reconnaissance coverage of wide oceanographic and littoral zones at a mission radius of 2,000 nautical miles. The UAS is designed to fly 24 hours a day, seven days a week with 80% effective time on station (see Triton website: <http://www.naval-technology.com/projects/mq-4c-triton-bams-uas-us/>).

Triton can be deployed in a range of missions such as maritime surveillance, battle damage assessment, port surveillance and communication relay. It will also have the capability to support other units of naval aviation to conduct maritime interdiction, anti-surface warfare (ASuW), battle-space management and targeting missions. These missions can be performed worldwide, including areas that are potentially populated with other air traffic. To conduct these missions safely and effectively in the vicinity of other air traffic, Triton depends on a layered defense strategy similar to that shown in Figure 2 (Lacher, Zeilin, Maroney, Markin, Ludwig, & Boyd, 2010). The outermost defense (i.e., procedural separation assurance) consists of a set of procedures and rules defined by oversight organizations such as the Federal Aviation Administration (FAA) and the International Civil Aviation Organization (ICAO) for safe operation in the National Airspace System (NAS) and international airspace. Simply



Figure 1 – MQ-4C Triton: Retrieved from <http://www.navair.navy.mil/index.cfm?fuseaction=home.display&key=7CD9F773-04D7-440F-AE35-653BBB7B288F>

adhering to these rules substantially reduces the chance of mid-air collisions. The middle ring of defense (i.e., tactical separation assurance) leverages air traffic services to maintain safe separation distances from other aircraft, and also uses specialized on-board systems to maintain safe distances from non-transponding (i.e., non-cooperative) aircraft. The inner-most ring includes shorter-range systems to avoid collisions for situations in which the two other defense layers fail. These systems advise the Triton operator of other near-by aircraft so that appropriate maneuvering actions can be taken.

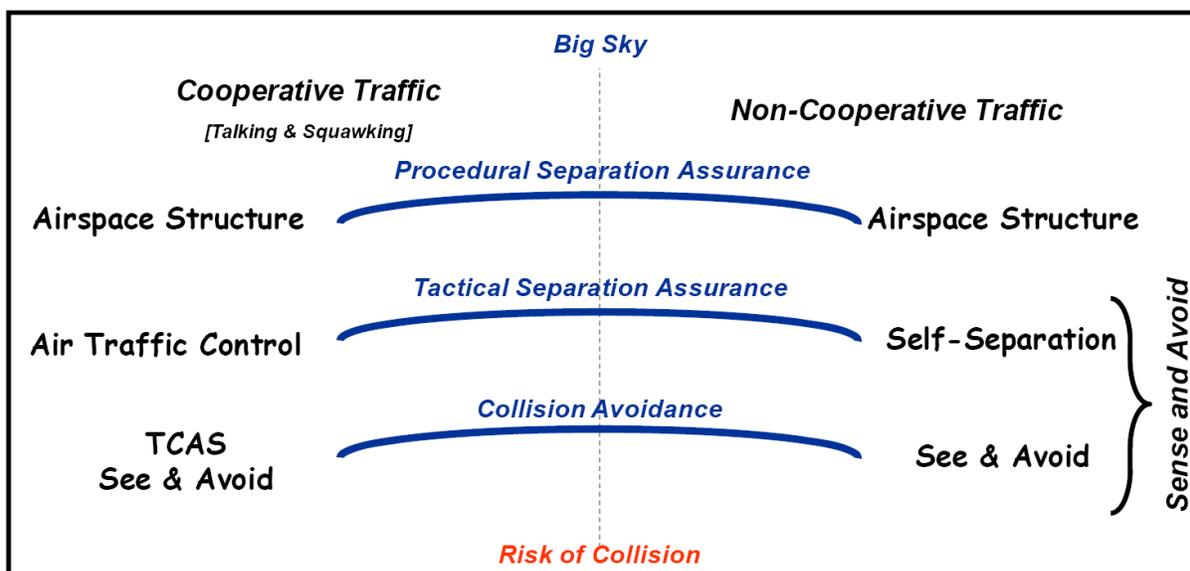


Figure 2 - Layered Approach to Avoiding Collisions

Since unmanned systems cannot “see and avoid” other aircraft, the FAA defined the term “sense and avoid” (SAA) to mean “the capability of an unmanned aircraft to remain well clear from and avoid collisions with other airborne traffic” (“Sense and Avoid (SAA) for Unmanned Aircraft Systems (UAS)”, 2009, p. 12). The Triton has two SAA sensor systems to self-separate from other aircraft (when air traffic services are not available) and to avoid collisions. The Traffic Alert and Collision Avoidance System (TCAS) is an interrogator-transponder system designed to increase cockpit awareness of proximate aircraft. Triton will be procuring the TCAS 3000 from Aviation Communication & Surveillance Systems (ACSS), which also includes Automatic Dependent Surveillance-Broadcast (ADS-B) (“TCAS 3000SP Description”, 2013). ADS-B makes use of GPS technology to determine and share precise aircraft location information, and streams additional flight information to the cockpits of properly equipped aircraft (“Automatic Dependent Surveillance-Broadcast (ADS-B)”, 2011). Triton will also be procuring its own collision avoidance radar to aid the Triton operator in avoiding potential encounters with non-cooperative

intruder aircraft. The characteristics of the operational environment that the UAS is operating within (e.g., airspace class, airspace density) define the relative importance of these sensors in achieving a defined Target Level of Safety (TLS) for Triton's missions. The elements of these three defense layers, together with the displays provided to the Air Vehicle Operator (AVO) at the ground station, collectively make up the Triton SoS for Airspace Integration (AI).

Although Triton has longer-term requirements for operations within the NAS, the immediate requirement is to conduct missions safely in oceanic environments when operating *due regard*. In this operational mode, the UAS operator must exercise due regard for the safety of navigation of civil aircraft, and implies that the UAS operator is taking responsibility for maintaining safe separation from other aircraft. The conditions and requirements associated with due regard operations are defined by DoD Instruction 4540.01 ("Use of International Airspace by U.S. Military Aircraft and for Missile/Projectile Firings", 2007).

There are numerous hazards that may affect the ability to conduct due regard operations safely and effectively. Triton is conducting a range of studies and analyses to demonstrate the effectiveness of solutions to mitigate these potential hazards, the foundation of which is referred to as the *Safety Case*. The Triton Safety Case is composed of a hierarchically organized set of safety claims each related to the ability to effectively mitigate some defined hazard. Associated with each claim is a set of evidence requirements which defines the nature of the evidence needed to substantiate that the claim is true. While those claims that focus on the hazard that some Triton system component is not meeting its performance and reliability requirements are generally best addressed through actual testing, many of the Safety Case claims focus on higher-level issues related to the ability of the entire Triton system to operate safely and effectively given that some defined hazard (or set of hazards) occur. This involves assessing whether the Triton AI SoS can effectively maintain self-separation distances from other aircraft across a wide range of different airspace characteristics (e.g., densities, altitudes) and potential hazards (e.g., system failures, degraded modes, weather, etc.). As discussed earlier, replicating all components of the SoS as well as the size and complexity of the airspaces Triton must operate within is cost-prohibitive to assess via live testing, and thus M&S is the tool of choice to produce the evidence needed to substantiate these SoS-level safety claims.

TRITON M&S TOOLS FOR SOS AIRSPACE INTEGRATION ANALYSIS

The diversity of products needed to satisfy Triton Safety Case evidence requirements requires an equally diverse but complementary suite of M&S tools. Some of these tools are faster-than-real-time (i.e., "fast-time") constructive M&S tools while other tools support direct interactions between human UAS operators and an immersive virtual M&S environment. The core applications in the Triton constructive M&S tool suite include the following:

Statistical Encounter Geometry Model: Evaluates encounters between unmanned aircraft (UA) and manned aircraft in arbitrarily complex airspace environments. The input to this model includes the flight paths of manned aircraft over a 24-hour period, using historical data sources from FAA established processes (e.g., offshore radar data, Advanced Technologies and Oceanic Procedures [ATOP] flight plan messages/position reports, Innovata data (formerly known as Official Airline Guide [OAG])). The UA flight path is also a model input. The model generates the rates at which encounters are expected to occur.

Due Regard Encounter Model: Describes the types of encounter situations that occur when operating due regard in an oceanic airspace for input to SAA system simulation evaluation. The model is based on Bayesian networks that represent the probabilistic relationship between variables that describe how aircraft behave in potential collision situations. FAA Enhanced Traffic Management Data (ETMS) is used as input to this model, which is produced from multiple sources (e.g., oceanic position updates, NAS messages, weather data, airline schedules). The model generates random aircraft trajectories that are statistically similar to those observed in the airspace. These trajectories represent the stages before a collision where the tactical due regard separation and collision avoidance functions would be invoked. The trajectory parameters include the relative positions, velocities, and attitudes of the aircraft up until the time of closest approach (Kochenderfer, Edwards, Espindle, Kuchar, & Griffith, 2010).

Collision Avoidance System Safety Assessment Tool (CASSATT): Performs fast-time analysis of aircraft encounters. Implemented in Matlab/Simulink, CASSATT leverages aircraft positional information predicted by the Due Regard Encounter Model and simulates aircraft encounters over a period of up to 10 minutes near the closest point of approach. Aircraft motion is represented using point-mass dynamics with acceleration constraints related to aircraft type. The performance of the aircraft sensors and collision avoidance systems (e.g., radar, TCAS, and ADS-B) are

monitored throughout the simulation. The probability of a Near Mid-Air Collision (NMAC) is computed for each simulation run based on the measured vertical and horizontal separation at the closest point of approach. These results are obtained for various encounter geometries, aircraft equipage, weather conditions, and avoidance strategies (Kuchar, 2005).

Collision Avoidance Sensor Trade Simulation (CASTS): Evaluates sensor requirements for reliably and safely conducting UAS missions in NAS and oceanic operational environments. Intended for rapid evaluation of very large tradespaces, the CASTS model is comprised of modules operating within the Open Extensible Architecture for the Analysis and Generation of Linked Simulations (OpenEAAGLES) framework. Examples of the modules typically used for UAS airspace integration analysis include aeronautical performance (provided by the BlueMax Aerodynamics Model), antenna, sensors (e.g., radar, ADS-B, and TCAS), tracker (Kalman or alpha-beta), and conflict avoidance algorithms. Inputs to the model include a wide range of independent variables, such as intruder aspect/speed/signature, maneuver type/rate, and system delay times. Outputs can also vary widely, including such metrics as horizontal/vertical miss distance, closest point of approach, and total time spent in an NMAC zone.

The virtual M&S tools being used in support of the Triton Safety Case include the following:

Joint Integrated Mission Model (JIMM): The main synthetic environment generator for Triton AI analysis. JIMM provides the Naval Air Systems Command (NAVAIR) Air Combat Environment Test and Evaluation Facility (ACETEF) with an ability to immerse external resources (e.g., hardware, software, other models, and people) in a simulated mission environment. The JIMM data protocols and shared memory interfaces allow rapid and reliable communication over both local and wide area networks. JIMM is highly flexible and general-purpose in nature, allowing scenario developers to create large numbers of disparate simulation entities with tailored and varying characteristics. During test events, JIMM can serve as a controller that commands and coordinates test article interaction with high fidelity stimulators. The simulation's data interface capability also allows people and/or other models to control JIMM-created entities as these entities interact with other simulation entities. JIMM inputs include definitions of system and scenario characteristics as well as entity behavior descriptions. JIMM can be instrumented to capture a wide range of output metrics applicable to AI analysis, including UAS operator performance information (e.g., time to recognize intruder threat, time to decide on maneuver, type of maneuver chosen).

High Fidelity Virtual Models: The representation of Triton aerodynamic performance and the SAA sensors to be used in the virtual exercises. Although the Triton constructive models also have representations of these same systems at a similar level of fidelity, these representations are all separate models operating on separate computers in the virtual environment interacting with the JIMM controller through local area networks. The Triton aerodynamic representation is a six degree of freedom (6 DOF) model derived from the Northrop-Grumman Corporation (NGC) Triton Closed Loop Simulator (CLS). NGC is also the source of the collision avoidance radar model, which is based on the real-time Radar Performance Model (RPM) used for design optimization and testing. The TCAS and ADS-B models are based on the designs of existing models developed by external organizations (e.g., NASA).

ADDRESSING THE M&S CHALLENGES

Management of Multiple Processes: There are several processes that must be properly coordinated to fully support the Triton Safety Case. For example, Triton employs a structured process to define and verify evidence requirements with claim "owners" (i.e., the individual or organization responsible for the satisfaction of the safety claim to ensure that evidence producers understand exactly what is required of them). A supporting analysis process translates the evidence generation requirements into an appropriate set of study methodologies and metrics. A scenario development process develops (or reuses) supporting concepts of Triton AI operation/employment and defines the vignettes needed to support the analysis. M&S development processes are exercised to create and/or extend the M&S infrastructure needed to enable the defined analysis methodologies. An M&S VV&A process is used to establish the credibility of the M&S infrastructure for the intended use. Finally, execution of the analysis methodologies requires a defined process for M&S employment to produce the metrics required to satisfy evidence requirements for the Safety Case.

Integrating these set of processes into a single coherent and coordinated master schedule across all SoS stakeholders is very difficult to do, since there is a considerable degree of concurrency, iteration, and dependency among the tasks that comprise these multiple processes. Triton manages the inherent complexity of multiple interacting SoS engineering processes through an overarching *process framework*. A process framework is a mechanism for

harmonizing disparity among low-level sub-processes and managing the associated complexities. Although there are many process frameworks supported by various organizations throughout the systems engineering community, very few are specifically tailored to the M&S domain.

The process framework that was chosen to support the Triton AI Safety Case is the Institute of Electrical and Electronics Engineers (IEEE) 1730 *Distributed Simulation Engineering and Execution Process* (see Reference 14). The IEEE 1730 standard is an end-to-end lifecycle process model intended to address the full range of activities needed to design, develop, integrate, test, and exercise a distributed environment of disparate LVC simulation resources (see Figure 3). Although the primary focus of this standard is on distributed simulation, the guidance provided by IEEE 1730 is generally applicable to standalone M&S as well. IEEE 1730 is actively maintained by both the IEEE and the Simulation Interoperability Standards Organization (SISO).

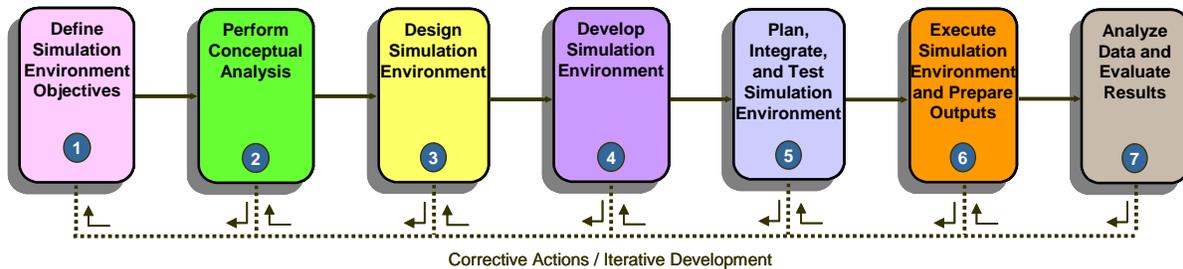


Figure 3 – IEEE 1730 Top-Level View

The mapping of the various supporting processes into this framework is described in the Triton AI Evidence Generation Management Plan (EGMP). This document associates each task in each supporting process with its corresponding activity in IEEE 1730.

The primary benefits of this mapping are:

- Ensures that the process used for Safety Case evidence generation on the Triton Program is based on an industry standard.
- Ensures that all core process elements (i.e., IEEE 1730 activities) are adequately addressed via the execution of one or more evidence generation tasks.
- Shows how multiple interacting processes (e.g., analysis, M&S development, VV&A) relate to one another in terms of how they support the core activities in the IEEE 1730 process framework.
- Identifies the tasks that must be included in the evidence generation Integrated Master Schedule (IMS). The collective state of the progress made on these tasks defines the overall state of the IEEE 1730 execution.
- Identifies output product(s) requirements for each evidence generation task based on the output product(s) associated with the IEEE 1730 activity to which the task is mapped.

The EGMP also associates each output product with the organization responsible for its production, the timeline for its development, and provides a hyperlink to the most current version of that product. This allows Safety Case managers to have immediate visibility into the set of products being produced, including who to contact if the state of completion of the product appears to be inconsistent with the IMS.

Mixed Fidelity: As stated earlier, there are numerous claims in the Triton AI Safety Case that focus on hazards related to Triton system components not meeting its performance and reliability requirements. In general, the satisfaction of these types of claims requires substantiating evidence drawn from live testing results. However, there are also safety issues related to how these system-level performance and reliability issues may affect the ability of the full Triton AI SoS to maintain defined separation distances while performing its missions. This requires injection of very high fidelity system emulations or actual system hardware into the lower fidelity M&S infrastructure typically used for mission-level SoS analysis.

The general application of M&S in the DoD T&E process is illustrated in Figure 4 (“Test and Evaluation Management Guide”, 2005). Triton Safety Case evidence generation is currently focused on Step 1, where M&S is being used to determine the effectiveness of the Triton AI SoS in mitigating system and operational hazards. An

especially critical output of this analysis is the operational conditions and System Under Test (SUT) configurations to be included in the test design (see Step 2). In Step 4, M&S is used to gain statistical significance of test results and to extend the set of test cases to a broader range of operational conditions.

Step 3 of this diagram refers to the test process itself, including test execution, analysis of test results, and post-processing of test results as needed to produce the metrics specified in the Safety Case evidence requirements. As the Step 3 block suggests, M&S can be used to stimulate test articles and provide the data streams needed verify that each SUT is satisfying performance and reliability requirements.

The Joint Unmanned Aircraft System Mission Environment (JUAS ME) provides many of the core infrastructure elements to support the Step 3 testing process (see Figure 5). JUAS ME is a Test Resource Management Center (TRMC) Central Test and Evaluation Investment Program (CTEIP) which is developing an immersive UAS test capability that models the effects of manned and unmanned aircraft cooperating in multi-platform mission environments. This includes the operational effects of real world data latencies, networking pathways, and theater operational restrictions. JUAS ME is ideally suited to addressing the mixed fidelity requirements associated with SoS analysis since it is designed to represent the full mission environment while providing the capability to insert SAA system hardware-in-the loop (HWIL) when higher-fidelity Safety Case evidence requirements dictate. JUAS ME is also designed to satisfy requirements to evaluate AI operational concepts across a wide range of national and international airspace characteristics, which is essential for planned Triton AI test activities (O'Day, 2012).

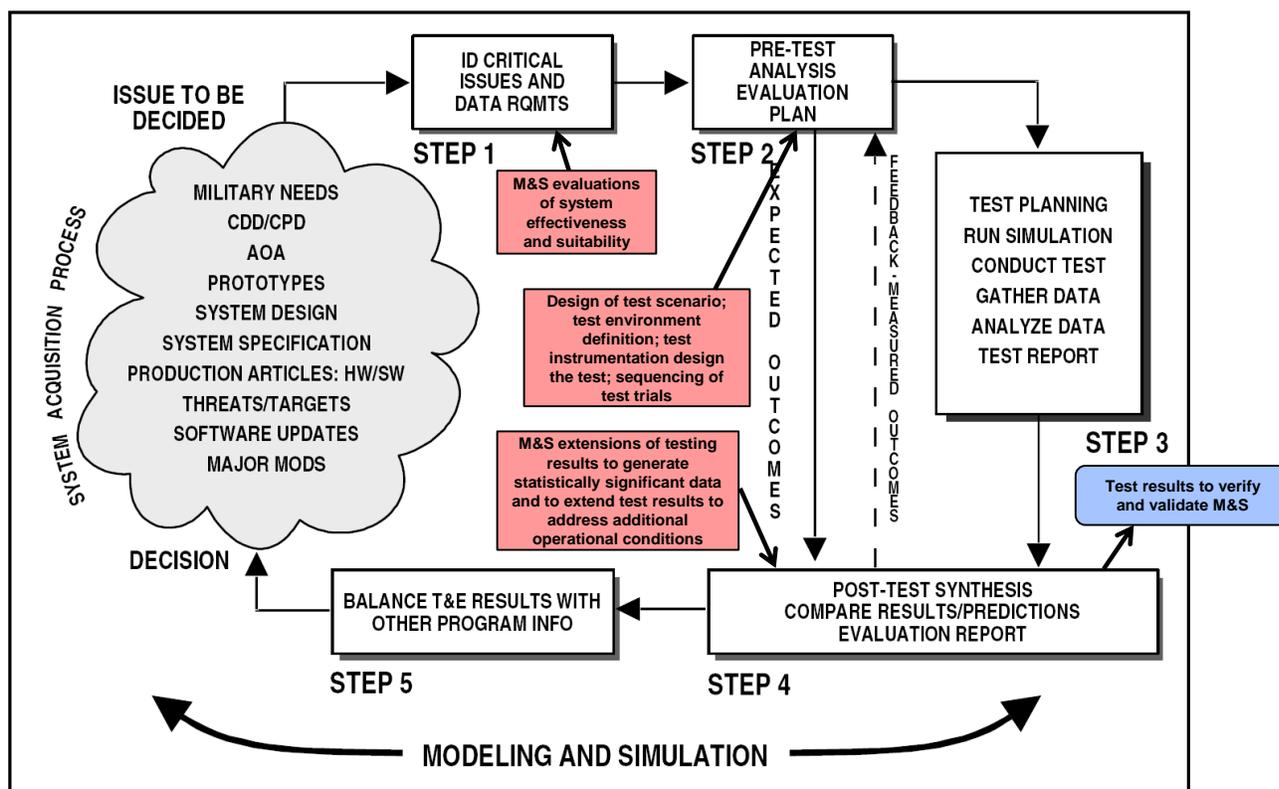


Figure 4 – M&S Overlay to the DoD T&E Process

Human Behavior: The large number of independent variables representing possible SoS configurations and the many variations of potential operational conditions requires extensive use of fast-time constructive M&S tools. However, SoS analysis is strongly influenced by the accuracy by which simulated humans are represented in these tools. Methods to ensure realistic simulated UAS operator behaviors and performance are needed to ensure the credibility of evidence generated in support of the Triton Safety Case.

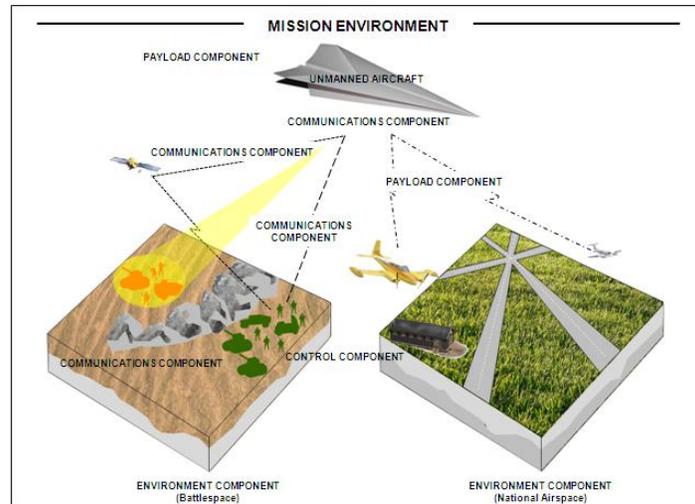


Figure 5 – JUAS ME Operational View

The Triton “Constructive-Virtual-Constructive” M&S strategy is shown in Figure 6. Early in the evidence generation process, a Design of Experiments (DOE) approach is used to evaluate a complete tradespace of independent variables using constructive M&S tools and a deterministic set of UAS operator rules validated by NAVAIR UAS operators. The results of this analysis are used to identify the hazards and operational conditions that represent the greatest threat to flight safety, which are then carried forward as use cases captured in the virtual M&S DOE. The execution of these use cases in the Triton AI virtual environment is then performed with extensive instrumentation of operator reactions. This instrumentation includes such factors as “time to identify potential encounter”, “time to decide on maneuver”, “maneuver chosen”, and “time to execute maneuver”. Multiple operators of varying background and experience participate in the virtual events to reduce the likelihood of bias in the measured operator data. As the virtual events progress, statistical distributions are developed to represent actual operator behavior and performance. Finally, the fast-time constructive M&S tools execute these same use cases using random sampling from the measured operator performance distributions rather than the less accurate deterministic operator rules. This preserves the benefits of fast-time constructive simulation for SoS analysis while significantly improving the fidelity of the underlying human behavior modeling.

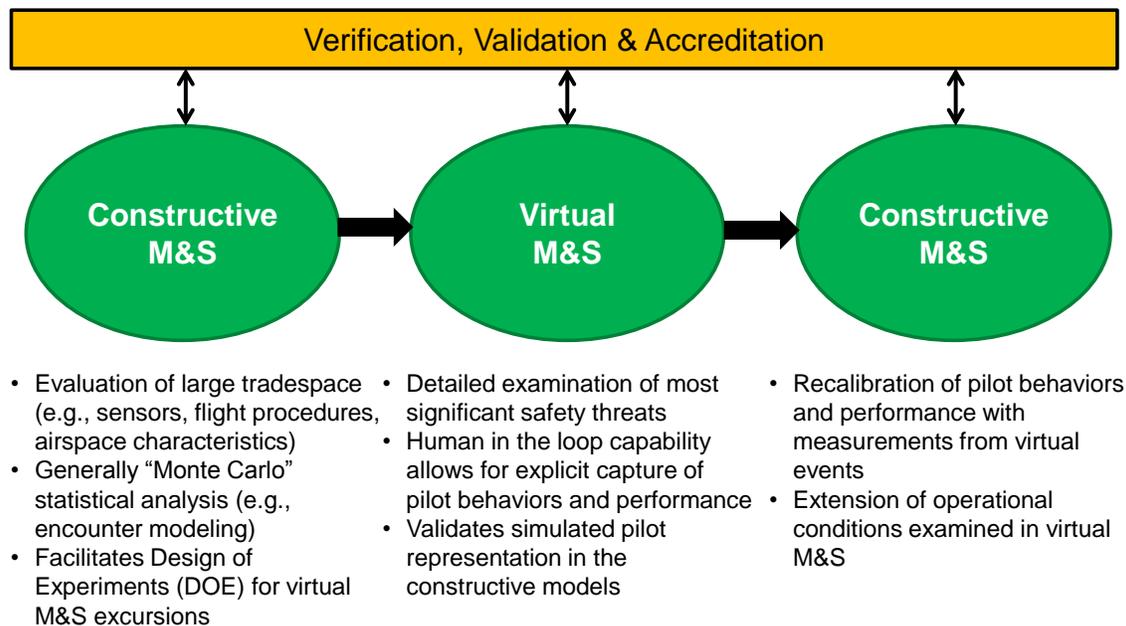


Figure 6 – Triton M&S Strategy for Safety Case Evidence Generation

The implementation of this strategy is illustrated in Figure 7. First, based on a defined set of Triton mission profiles and an extensive set of airspace characteristics derived from FAA sources, the fast-time constructive tools produce the data needed to inform the virtual M&S DOE. This includes encounter probabilities, encounter rates, encounter geometries, and tradespace analysis results. As the virtual use cases are defined, they are executed in the ACETEF UAS Integration Laboratory (UASIL) using JIMM as the synthetic environment generator and a Triton MCS emulator as the interface with the UAS operator. As the operator distributions are developed, they drive the operator representations resident in the CASTS and CASSATT models. It is the execution of the use cases in these tools that generate the statistically significant data that fully satisfies the defined evidence requirements and ultimately verifies that Triton TLS requirements can be met.

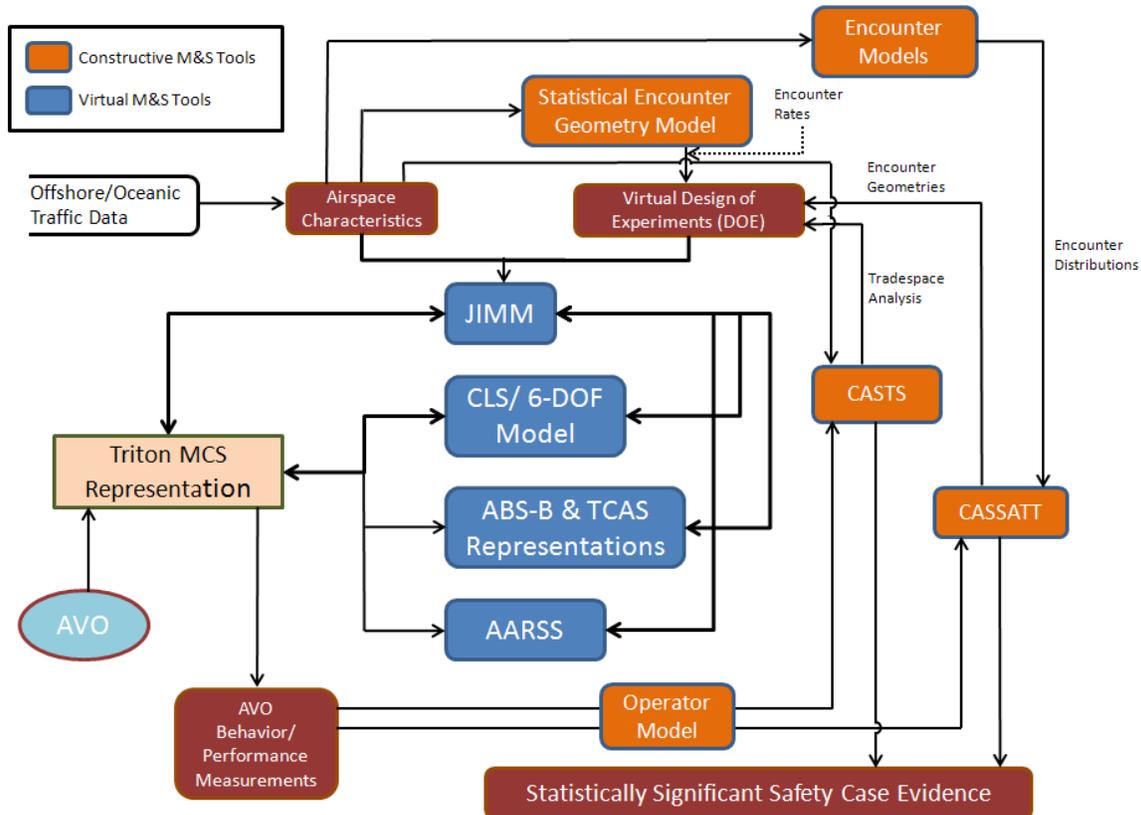


Figure 7 – Triton AI M&S Architecture

Verification, Validation, and Accreditation (VV&A): The Triton AI SoS places an unusually heavy emphasis on M&S for producing substantiating evidence for claims in the Safety Case. This is mainly due to the very high cost of replicating the complexity of the airspace in which the Triton SoS will operate on a live range. However, inaccurate M&S predictions of the ability of the Triton operator to mitigate defined hazards in that environment may have significant consequences for flight safety. Thus, accreditation of the Triton AI M&S environment requires a comprehensive, robust set of supporting V&V evidence. Production of this evidence requires a highly controlled VV&A process that addresses all aspects of how the SoS and its operational environment are represented.

The Triton M&S VV&A process is managed by NAVAIR's Battlespace Modeling & Simulation Division (Code 5.4.2.3), and represents an appropriate tailoring of the guidance provided in the DoD M&S VV&A RPG. A simplified illustration of this process is shown in Figure 8. As the model user identifies M&S requirements based on analysis objectives, the VV&A team works with the model user to define appropriate acceptability criteria and associated metrics for verifying that each M&S requirement is met. The Triton VV&A team then compares existing V&V evidence for that tool against the acceptability criteria and estimates the risk associated with using the M&S tool to satisfy the analysis objectives. This information is captured in an Accreditation Plan that defines what additional V&V evidence is needed to reduce risk to acceptable levels. The model user then develops a plan for producing the required V&V data and executes it. The augmented set of V&V data, along with a revised risk

assessment, is then captured in an Accreditation Support Package from which a summary report is generated. The summary report, along with an accreditation recommendation, is then provided to the Triton AI M&S accreditation authority for approval and signature.

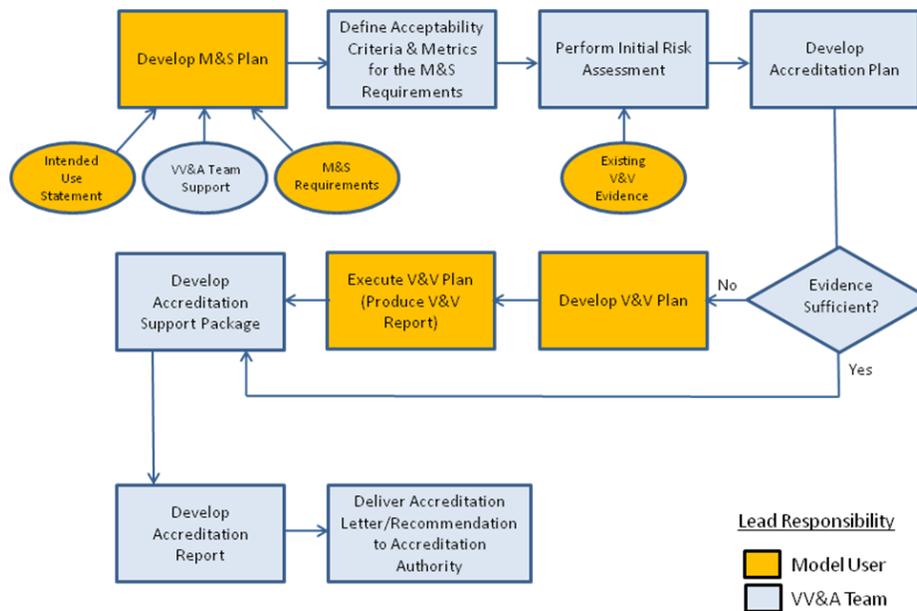


Figure 8 – Triton VV&A Process

Although this process is consistent with standard DoD VV&A practices, execution of this process for SoS analysis introduces some additional complexities. The full range of analyses needed to support the Triton Safety Case is partitioned into a set of studies, each intended to provide substantiating evidence for some related set of safety claims. For instance, there may be a study to examine mitigation strategies related to the impact of sensor hazards on overall SoS performance, while a different study may examine potential communication hazards. The analysis methodology defined for each study requires an appropriate mix of fast-time constructive M&S tools and real-time virtual M&S tools to gain the proper insight into the various issues and potential solutions. Because the mix of M&S assets is different for each study, M&S VV&A planning is performed at the level of the entire study rather than for each individual tool. Thus, acceptability criteria for verifying that M&S requirements are being met is defined across all of the selected M&S assets in a single study-specific Accreditation Plan. This allows acceptability criteria to be defined not only for required capabilities provided by individual M&S tools, but also for how the individual M&S applications must share information and (in some cases) directly interact at runtime to accurately represent the SoS-level capabilities needed to support study requirements. While the owners of the M&S tools identified to support the study can produce V&V plans at the individual tool level, the need to provide V&V evidence for the way their models interface with other models as needed to represent higher-order SoS behaviors is a critical element of all V&V plans.

Execution of the various V&V plans requires considerable coordination among the model users. To verify the runtime model interfaces, data collection requirements defined in the V&V plans are addressed via appropriate instrumentation at periodic test events to ensure that the supporting models are interoperable and can represent the SoS and surrounding airspace accurately. Since live range measurements of SoS performance and behavior is difficult (if not impossible) to obtain, Subject Matter Expert (SME) review of results from selected vignette executions is generally the validation method of choice. For fast-time M&S tools, models that generate input values for other models (to capture all the relevant aspects of the SoS) are included in the scope of VV&A activities, since credibility depends on the combination of the tools and its supporting dataset. The assemblage of all V&V data for both the capabilities provided by individual models and the composite capabilities provided by the model interactions collectively provides the core V&V body of evidence needed for accreditation of the M&S infrastructure for SoS analysis.

STATUS/NEXT STEPS

The SoS analysis required to address evidence requirements in the Triton Safety Case is well underway. Most FY13 activities are focused on the development, accreditation, and execution of the constructive fast-time tools to inform the virtual M&S DOE. In FY14, the focus will shift to the virtual executions, with separate events planned to examine mitigation strategies related to sensor and communication hazards as well as operator workload issues. In FY15, the results of the virtual events will be used to parameterize the operator models in the fast-time constructive tools in order to generate statistically significance Safety Case evidence with high-fidelity operator representations. The goal is to complete the Triton SoS Safety Case analysis in time for Triton to be formally certified for due regard operations by late FY15.

CONCLUSIONS

There are many challenges associated with evaluating the performance of a SoS in a multifarious operational environment. M&S is a widely recognized enabler of the analyses needed to determine SoS performance, but the specific M&S capabilities needed to represent the inherent complexity of a SoS architecture as well as the diverse combinations of operational conditions that the SoS may need to operate within can be extremely challenging to develop, integrate, and employ. This paper has described how many of these challenges were addressed within the context of UAS airspace integration, and how meeting those challenges allowed the Triton Program to produce statistically significant data supporting risk assessment, Safety Case development, and due regard certification.

Although the innovations described in this paper have been developed in support of the Triton Program, there are many government organizations that can benefit from this capability. Certainly organizations that conduct investigations into UAS airspace issues can reuse significant aspects of the framework, processes, and M&S infrastructure developed by Triton, including the FAA, the Department of Homeland Defense (DHS), the National Aeronautics and Space Administration (NASA), and other DoD UAS programs. Still other government agencies can reuse much of this work in support of various Concept of Operations (ConOps) development and system requirements validation activities.

ACKNOWLEDGEMENTS

The authors would like to thank Paul Frederick for his leadership of the Triton AI team and for his support throughout the development of this paper. The authors would also like to thank the many contributors to the M&S infrastructure that currently supports the Triton Safety Case. Although the list of these contributors is quite long, a special thanks to Jesse Mrozowski and Steve O'Day of NAVAIR 5.4, Kim Wasson, Tony Aiello, and John Knight of Dependable Computing, Tony Pucciarella and Mike Collins of Ausley Associates, Michael Gilbert of MITRE, James Shedden and Jeremy Warren of Booz Allen Hamilton, and David Turner of SURVICE Engineering.

REFERENCES

1. "Systems Engineering Fundamentals" (2001). Defense Acquisition University (DAU) Press.
2. "Joint Capabilities Integration and Development System", Chairman of the Joint Chiefs of Staff (CJCSI) 3170.01E (2005). U.S. Department of Defense, Washington, DC.
3. "Requirements Management in a System-of-Systems Context: A Workshop" (2006). Carnegie-Mellon Software Engineering Institute, CMU/SEI-2006-TN-015.
4. Dahmann J., Lane J, Rebovich G., Baldwin K., "A Model of Systems Engineering in a System of Systems Context" (2008). Sixth Conference on Systems Engineering Research.
5. "Systems Engineering Guide for System of Systems" (2008). ODUSD(A&T) Systems and Software Engineering, Version 1.0.
6. Piplani L., Mercer J., Roop R., "Systems Acquisition Manager's Guide for the Use of Models and Simulations" (1994). Defense Systems Management College.
7. Lacher A., Zeilin A., Maroney D., Markin K, Ludwig D., Boyd, J., "Airspace Integration Alternatives for Unmanned Aircraft" (2010). AUVSI Unmanned Systems Asia-Pacific.
8. "Sense and Avoid (SAA) for Unmanned Aircraft Systems (UAS)" (2009). Federal Aviation Administration.
9. "TCAS 3000SP Description" (2013). ACSS website, <http://www.acss.com/products/tcas-3000sp/>.

10. “Automatic Dependent Surveillance-Broadcast (ADS-B)” (2011). FAA website, <http://www.faa.gov/nextgen/implementation/programs/adsb/>.
11. “Use of International Airspace by U.S. Military Aircraft and for Missile/Projectile Firings” (2007). DoD Instruction 4540.01.
12. Kochenderfer, M., Edwards, M., Espindle, L., Kuchar, J., Griffith, J., “Airspace Encounter Models for Estimating Collision Risk” (2010). *Journal of Guidance, Control, and Dynamics*, Volume 33, Issue 2, Pages 487-499.
13. Kuchar J., “Safety Analysis Methodology for Unmanned Aerial Vehicle (UAV) Collision Avoidance Systems” (2005). FAA/EUROCONTROL Air Traffic Management (ATM) Seminar.
14. “IEEE Recommended Practice for Distributed Simulation Engineering and Execution Process (DSEEP) (2011)”. IEEE Standard 1730-2010.
15. “Test and Evaluation Management Guide” (2005). 5th Edition, Defense Acquisition University Press.
16. O’Day, S., “Joint Unmanned Aircraft Systems Mission Environment (JUAS ME) Project Overview” (2012). UAS Coalition Conference.