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FROM THE EXECUTIVE EDITOR

WELCOME to the Winter 2013/2014 issue of the *M&S Journal,* with a focus on modeling and simulation (M&S) support to acquisition. As described in the guest editorial by Dr. Wood, the use of M&S to support acquisition activities has not always met expectations—the ability to ascertain how various capabilities influence the battlefield, optimize entire system designs, or perform virtual testing are certainly worthy goals, but always seems to be on the horizon. However, there are excellent examples of M&S already providing valuable support to acquisition, as you will see described in this issue's articles.

The history of applying the power of computing to design began in the 1960's with the first tools for developing integrated circuits and supporting software engineering. As one of my computer science professors was fond of saying, "Today we could not design computers without the use of computers." On a macro level, there are many examples of M&S supporting commercial manufacturing and production processes. In the 1990's, the Chrysler Corporation developed algorithms and simulations for its product and process lifecycle management system that enabled the company to reduce its production costs to less than half of the industry average. Today, many commercial manufacturers routinely use simulations to explore alternative production line scenarios for improving assembly line efficiency. As a case in point for the defense industry, the Department of Defense (DoD) Joint F35 Lightning II program used the Dassault Systèmes DELMIA® production line simulation, considered one of the most efficient for aircraft production to develop its aircraft manufacturing line.

The articles in this issue of the *M&S Journal* demonstrate the value in applying M&S to DoD acquisitions. In the article, "Vehicle and Sensor Performance Tradeoff Study with the Virtual Autonomous Navigation Environment," Dr. Goodin et al. provide a use-case for applying physics-based simulations to explore the trade-space between sensor and vehicle performance. A related article, "U.S. Army Sensors Life Cycle Acquisition with Modeling & Simulation," offers a similar larger scale exemplar of using simulation tools.

While the application of M&S in support of the acquisition process has advantages, it should not be considered an across-the-board solution for all situations. The utility and acceptance of M&S in support of the acquisition process depends on thoughtful applications. The article by Dr. Morse et al. addresses the complexity of system of system (SoS) analysis; compares/contrasts the M&S requirements for analysis, training, and testing; and then identifies the benefits and drawbacks of applying live-virtual-constructive (LVC) M&S to SoS analysis. Similarly, the article by Mr. Tritsch et al. guides users in the identification and appropriate application of M&S standards. Finally, the three articles by Dr. Colombi et al., Dr. Johnson and Dr. Ferguson, and Mr. Iacchei and Mr. Houck demonstrate the use of simulation to reduce cost and risk—a significant motivation for the use of M&S.

While the potential of M&S in support of acquisition may not be fully realized, I think you will discover within this issue that much has already been accomplished to assist and improve the acquisition community's needs. Lastly, from myself and the editorial board, many thanks to our guest editor from the Defense Acquisition University, Dr. Wood, and to the authors for their contributions to the *M&S Journal.*

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Guest Editorial: Acquisition

Guest Editor

Dr. Roy L. Wood
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OK, I WILL ADMIT UP FRONT THAT AS AN ACQUISITION GUY, I'VE ALWAYS HAD A LOVE-HATE RELATIONSHIP WITH MODELING AND SIMULATION (M&S). THERE. I'VE SAID IT. FULL DISCLOSURE. MAYBE A BETTER WAY TO PUT IT IS THAT I LOVE THE PROMISE AND POTENTIAL OF M&S. I GET EXCITED JUST THINKING ABOUT THE ABILITY TO PUT A NEW IDEA FOR A PIECE OF HARDWARE THROUGH ITS VIRTUAL PACES TO SEE HOW IT MIGHT PERFORM ON THE BATTLEFIELD. I LOVE THE PROSPECT OF USING A SIMULATION TO SHORTEN THE TEST CYCLE AND REDUCE TEST EVENTS AND RESOURCES. BUT DOES THIS REALLY HAPPEN? YES, CERTAINLY IN ENOUGH CASES TO HOLD MY INTEREST AND EXCITEMENT. BUT SADLY, NOT OFTEN ENOUGH TO CONVINCE ME THAT WE'VE REACHED VIRTUAL NIRVANA.

Allow me to share a few stories that helped shape this view of modeling and simulation (M&S) and maybe some lessons I learned along the way…

In graduate school, I had a close encounter with my first M&S opportunity. My thesis advisor assigned the seemingly simple task of porting a Fortran-based control system sim from our mainframe to the brand new IBM-PC. After a few weeks of futile attempts, I scrapped the idea of portability and rewrote the entire program in Turbo Pascal. That was my first lesson in hardware and software compatibility, portability, and "reusable" code.

I believe these kinds of issues continue to challenge the larger M&S community. Pockets of M&S excellence sprout up around a well-funded project, but the resulting code may not be portable to other acquisitions. Since that long-ago graduate project, the state-of-the-art in software design has advanced on to object-oriented programming with its promise of modularity, encapsulation, and reuse. Will this and other innovations revolutionize how models and simulations are written and deployed, or like Sisyphus repeatedly pushing his boulder up the hill, is the community doomed to write and rewrite M&S routines from scratch? From my own painful experience, I hope the community is embracing ways to truly write once, use many.

GUEST EDITOR
Dr. Roy L. Wood
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My next opportunity to delve into the M&S world was during an assignment at the High Energy Laser Systems Test Facility (HELSTF) on the White Sands Missile Range in New Mexico. Some very good work had been done on laser propagation models at prestigious university laboratories. These models predicted with uncanny accuracy the energy-on-target in many operating regimes. However, an anomalous phenomenon called thermal blooming was predicted to occur when the laser beam remained focused through a static column of atmosphere. The laser heated the atmosphere,

creating lensing effects—think desert mirage—which caused a loss of much of the beam's energy on target. How much? Different models predicted different values and the math in some models simply gave up or blew up. So, we did a series of experiments to help anchor the codes. On our first test, the lensing effects were present but really didn't have the dramatic effect on the performance on target. When the test results were presented, one of our model-masters angrily retorted, "That couldn't possibly have happened; the results are completely at odds with our model!"

Models, however sophisticated, have their limitations. That's OK. Models and simulations are only ever approximations of reality. As statistician George Box noted in 1987, "All models are wrong but some are useful." At the end of the day, models mainly exist to support decisions—decisions about design, operations, capabilities, and limitations of real life systems. The HELSTF models helped us decide on how best to design a live laser test and then extend those results to predict how the system might perform in other, similar test regimes. This was important because live tests cost hundreds of thousands of taxpayer dollars and we were able to avoid actual testing by confidently using the modeled predictions.

In acquisition, we need M&S for the same purpose. If we can build models that accurately predict system performance in a variety of regimes, then we can avoid the cost and time of more extensive live testing. The models don't need to be perfect, just good enough to support reduced-risk acquisition decisions on design, capability, and operational suitability. For instance, if we can fly a limited number of new missiles in live tests and then use M&S to "fill in" other likely operational scenarios, we can build confidence in the system at a substantially lower cost than firing hundreds of real missiles. And saving money is a good thing, especially in times like these of declining budgets. The ideas also align well with the affordability initiatives outlined in Better Buying Power, championed by Under Secretary of Defense Frank Kendall.

But...to achieve real affordability, the models themselves need to be affordable. This has implications for how we build the models. They have to be accurate, but need not be gilded with cool bells and whistles. Added complexity not only has cost implications but, as Leo Breiman warns in 2001, "...as data becomes more complex, the data models become more cumbersome and are losing the advantage of presenting simple and clear pictures of nature's mechanism." Complicated models are difficult and costly to build, maintain, and explain. Simpler is usually better for everyone.

Finally, I will relate an extraordinary success story related to the Navy's AEGIS Ballistic Missile Defense system. AEGIS engineers took what was essentially a 1960s tactical anti-missile system design and morphed it into a 21st Century capability to track and engage exo-atmospheric ballistic missiles with its new SM-3 missile and hit-to-kill warhead. During testing, these high-altitude intercepts were evaluated using reams of remote telemetry. Analysts combed through the data and assessed hundreds of critical flight events. Outbriefs were insightful, but unimaginably dry. Then, AEGIS engineers decided to use the telemetry to create a stunning visualization of the missile flight. Like a scene from the movie "Dr. Strangelove," the observer could now ride along with the interceptor missile, watching its maneuvers and gyrations as it precisely positioned itself in the path of the oncoming enemy. That simulation was a game-changer in terms of transforming skeptics into raving fans. If a picture is worth a thousand words, then a simulation video can extend that by orders of magnitude.

As an acquirer, I offer that the acquisition community needs and values the work M&S professionals do. You can be force multipliers when you work your virtual magic. I encourage you to work closely with program managers and engineers to build models and simulations that help them make smarter design, engineering, and test decisions. Be proactive in finding out just how much fidelity is really needed and aim for that. Remember that exquisite can be the enemy of good enough. Finally, as acquisition budgets shrink, look for ways to avoid building and rebuilding custom models and simulations from scratch; develop sharable and reusable code. Keeping these ideas in mind will be critical to our mutual success in delivering effective and affordable systems to our warfighters in the field in the future.

By the way, I know most of your best work happens behind the scenes without much fanfare or recognition. So, here in public, let me say from all the acquisition professionals you support—thanks for all you do!

Guest Editor's Biography

Dr. Roy L. Wood, Jr.

Dr. Roy L. Wood, Jr. is the dean of the Defense Systems Management College and School of Program Managers at the Defense Acquisition University. He is responsible for training senior military and civilian acquisition leaders.

Prior to this assignment, Dr. Wood was the principal assistant deputy undersecretary of defense for International Technology Security. Dr. Wood also worked for five years in industry, supporting the Navy's Above Water Sensors program, including the startup and execution of the Cobra Judy Replacement program. This complex, $1.5 billion acquisition included development of two new high-power phased array radar systems and integration of those onto a commercial-class ship.

Dr. Wood retired from the Navy in May, 2001 after 24 years of enlisted and commissioned service. His operational assignments included tours in submarines and surface ships. As a Naval engineering duty officer, he also served as a project manager in a Naval Shipyard; operations officer and test director for the Navy's high-energy laser prototype in New Mexico; a senior system engineer in the AEGIS weapons system program office; and branch chief for advanced surveillance systems at the Ballistic Missile Defense Organization (now Missile Defense Agency).

Dr. Wood holds degrees in computer science, electrical engineering, and business. His Ph.D. is in organization and management.

Vehicle and Sensor Performance Tradeoff Study with the Virtual Autonomous Navigation Environment

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Abstract

THE VIRTUAL AUTONOMOUS NAVIGATION ENVIRONMENT (VANE) IS A COMPUTATIONAL TEST-BED (CTB) DEVELOPED BY THE U.S. ARMY ENGINEER RESEARCH AND DEVELOPMENT CENTER (ERDC) TO PERFORM HIGH-FIDELITY, PHYSICS-BASED MODELING AND SIMULATION OF SENSORS AND GROUND VEHICLES USING HIGH PERFORMANCE COMPUTERS. THE VANE-CTB USES RAY-TRACING TO MODEL REALISTIC PERFORMANCE FOR SENSORS SUCH AS CAMERAS, GLOBAL POSITIONING SYSTEM (GPS), AND LIGHT DETECTION AND RANGING (LIDAR) SENSORS. THE VANE-CTB ALSO INCORPORATES THE OUTPUT OF 3-D THERMAL AND HYDROLOGICAL SIMULATIONS TO ACCURATELY MODEL SOIL SURFACE TEMPERATURES.

TO DEMONSTRATE THE VALUE OF THE VANE-CTB TO MODELING AND SIMULATION (M&S)-BASED ACQUISITION, A USE-CASE WAS SELECTED TO EXPLORE THE TRADE-SPACE BETWEEN OPTIMAL SENSOR AND VEHICLE PERFORMANCE THROUGH A SERIES OF PHYSICS-BASED SIMULATIONS. IN THESE SIMULATIONS, AN INFRARED SENSOR WAS MOUNTED ON A HIGH-MOBILITY MULTIPURPOSE WHEELED VEHICLE (HMMWV) AT SEVERAL HEIGHTS AND WITH TWO DIFFERENT LENS CONFIGURATIONS. THE INFRARED (IR) SENSOR WAS USED TO DETECT REGIONS OF DISTURBED SOIL, POTENTIALLY INDICATING BURIED THREATS, IN THE ROADBED. THE MOUNT HEIGHT IS RELATED TO THE STANDOFF DISTANCE OF THE DETECTOR, WHICH IN TURN LIMITS THE MAXIMUM SPEED THE VEHICLE IS ABLE TO MAINTAIN WHILE STILL BEING ABLE TO STOP SAFELY WHEN A POTENTIAL THREAT IS DETECTED. BY QUANTIFYING THIS RELATIONSHIP BETWEEN SENSOR PERFORMANCE AND MAXIMUM VEHICLE SPEED, THE OPTIMAL SENSOR MOUNT POSITION CAN BE DETERMINED IN LIGHT OF THE VEHICLE'S REQUIREMENTS.

Introduction

Vehicle systems equipped with forward-looking sensors capable of detecting potential buried threats could provide a means of mitigating the risk posed by traveling uninspected roadways. Several basic principles of forward-looking, vehicle-mounted sensors constrain the application of these types of sensors. Among these constraints is the look-ahead or standoff distance of the sensor.

The standoff distance in this work refers to the average range at which a sensor can detect a target. If the purpose of the sensor is to detect threats that would cue a driver to stop, then the standoff distance of the sensor and the maximum vehicle speed are related by the distance it takes the vehicle to stop based on speed. For example, if the stopping distance of a vehicle traveling at 100 m/s (30 mph) is 60 meters (200 feet), then the standoff distance must be at least 60 meters.

Figure 1: The scenario simulated in this work was for an IR sensor mounted on a wheeled vehicle

One potential method for detecting shallow buried threats is to use an infrared (IR) sensor to detect roadbed sections with anomalous thermal signatures. In this paper, we discuss a hypothetical scenario in which an IR sensor is mounted on the front of High-mobility Multipurpose Wheeled Vehicle (HMMWV) and then explore through simulation, the optimal sensor mount height for detecting a shallow buried threat. A visualization of the scenario is illustrated in figure 1. The Virtual Autonomous Navigation Environment (VANE), a collection of simulation tools including sensors, terrain, and vehicle dynamics, was used to simulate the entire end-to-end sensor-environment interaction. Finally, analysis explains how predicted detection rates can be used to determine the optimum sensor standoff, thereby constraining the maximum vehicle operating speed.

Experiment Details

In the simulated experiments, a camera was mounted on a HMMWV that was driven along a raised dirt roadbed which had a region of disturbed soil representing a shallow buried threat. In figure 2, the disturbed region can be seen as a bright spot near the center of the image. The digital terrain represented an area at Fort Carson, CO. Great care was taken to capture the physical detail of the real-environment while preserving the physics of the thermal and camera simulations.

Thermal simulation

The temperatures of the terrain and vegetation in the scene were determined using high-fidelity, physics-based simulation of geo-environmental factors influencing soil temperatures to accurately reproduce IR sensor data. The computational suite of tools [1], [2] developed under Army Technology Objective (ATO) Geo-environmental Tactical Sensor-simulation Tool (GEOTACS) simulates the thermal response of an approximately 100-meter strip of dirt roadbed, as shown in figure 2.

Digital Terrain Generation

The simulation was conducted on a virtual digital terrain of a small dirt road at Fort Carson near Colorado Springs, CO. The surface mesh was constructed from light detection and ranging (LIDAR) data collected at the site. The resulting point cloud file was uploaded into the PointsBuilder software, part of the Computational Model Builder (CMB) [3] suite of tools.

Figure 2: Simulated grayscale image of the physical temperatures in the simulated region. The target region is circled in yellow.

The raw LIDAR scan contained points from the land surface and surface vegetation. PointsBuilder segmented the LIDAR data and separated the LIDAR scans of vegetation from those of the surface. A surface mesh was created for the modeled region using the SceneBuilder program, another CMB module. A volume of interest, representing the area created for the surface mesh, was determined for the area modeled for the simulations. The surface mesh scene was generated with a user-specified mesh length and elevation weighting radius. These parameters allowed for the smallest surface resolution while keeping the surface as smooth as possible. After the surface mesh was constructed, a volume mesh was constructed using the ModelBuilder program, another CMB tool. To create the simulation input files, ModelBuilder was used to specify variables such as time-step size, top surface flux, pressure head, and temperature.

The material properties for each soil type collected in the field were assigned to the appropriate regions of the volume mesh. Table 1 presents a partial list of the soil properties values assigned to the different regions of the volume mesh.

Property	Undisturbed Soil	Disturbed Soil
Porosity	0.28	0.28
Hydraulic Conductivity	0. 0657	0.0657
Specific Storage	0.000001	0.000001
Solid Specific Heat	0.00016	0.000219
Solid Specific Gravity	2.65	2.65
Albedo	0.35	0.35
Bulk Emissivity	0.95	0.95
Dry Thermal Conductivity	0.3532	0.3532
Sat. Thermal Conductivity	2.1887	2.1887
Fraction of Sand & Gravel	0.925	0.925
Residual Saturation	0.01	0.01
Quartz Fraction	0.45	0.45
Flow Refine Tolerance	0.2	1.00000

Table 1: Partial list of soil properties used in the thermal simulation

The vegetation models were produced using the Greenworks Xfrog suite using measurements taken in the field of the typical branching patterns, branching angles, and tree heights. The vegetation models were then exported as object files (.obj) for use in the CTB. To keep the size of the simulation down, the resolution of many of the vegetation models were reduced while still retaining significant detail. Most of the vegetation models lacked foliage due to the time of year that measurements were taken and therefore required a high level of detail to display small order branching to obtain an optimal level of realism for the shadows.

The CMB's SceneBuilder program was used to place the different species of vegetation in the synthetic scene. First, the LIDAR point-file, extracted from the raw scans, was imported into the program. Then the "Snap Target" filter was applied to the surface so that the base of the vegetation would be accurately placed at the correct elevation. The vegetation was randomly oriented by applying different rotations and scales in the graphical user interface (GUI) to cast accurate shadows in the modeled scene.

Meteorological data for Fort Carson, CO was collected to provide the environmental context for the simulation. The meteorological station records the latitude, longitude, and elevation of its location and collects atmospheric data including barometric pressure, air temperature, relative humidity, wind speed, and wind direction at 2.0 and 0.5 meters. The meteorological station also collected soil data including volumetric water content, total precipitation, soil heat flux (soil temperature at various depths), incoming shortwave radiation, and downwelling longwave radiation. All of these properties were incorporated into the thermal simulation to yield the most realistic results possible.

Physics Models

The Adaptive Hydrology (ADH) [4] code was used to simulate the moisture flow in this simulation. ADH is a finite element model used to simulate partially-saturated flow and heat transport in 3-D for soils and other materials. It is coupled to a 2-D surface water flow model on the surface of the soil mesh. The ground water and surface water exchange explicit elemental fluxes during a given time step. The surface heat exchange includes shortwave

input, longwave input, longwave output, sensible heat, latent heat, and precipitation heat. ADH uses a fully 3-D tetrahedral finite element mesh comprised of all scene elements that conduct heat with the subsurface. The ADH model couples with the radiative transfer and vegetation models to produce volumetric and surface soil moistures and temperatures.

The vegetation model simulates the energy budget components in a canopy soil system. The vegetation objects are modeled as discrete elements over the soil mesh. These 3-D geometric representations of plants simulate shadows and the energy balance on the visible portions of the plant. Energy variations for these discrete elements are described in terms of the net radiation, sensible and latent heat, and ground heat fluxes. Temporal variations of sensible and latent heat fluxes are modeled by linking them to the measured wind speed and relative humidity. The stomatal resistance submodel is approximated by using air temperature, relative humidity, global radiation, and vegetation type.

Sensor Simulation

The IR sensor simulation was performed using the VANE high-fidelity, parallel ray-tracing software that was written by the ERDC to use high-performance computing (HPC) in physics-based sensor simulations. This ray-tracing tool can simulate a variety of sensors including cameras, LIDAR, and GPS [5]-[7]. The ray-tracer accurately captures surface reflectance properties and shadowing. In this simulation, the temperatures were generated using the thermal simulation; the ray-tracer used the nodal temperature values to calculate the emissive energy of each triangle in the scene using the material properties of the surface and vegetation elements and Planck's equation.

The camera was a longwave IR system covering the 7.3-13 micrometer wavelength range and had a 640x480 pixel resolution. Two lens configurations were used. The first lens had an opening angle of 45 degrees, while the second had an opening angle of 65 degrees. For each lens configuration, seven mount heights from 3-9 meters in 1-meter increments were simulated. Clearly, a mount height of 9 meters is not realistic for a HMMWV. However, higher mount heights were considered to fully explore the parameter space.

More than 4,000 images were generated from the simulation, with the HMMWV starting at one end of the dirt road and driving to the other end while taking video at ten frames per second. The target was not visible in most of the images; only the images in which the target was visible were considered for this analysis. Once the images for the 14 different configurations were completed, and the Reed-Xiaoli anomaly detector (RXD) algorithm was used to analyze each image and determine if the target could be detected in the image.

RXD Algorithm

The RXD [8] is most often used algorithm for anomaly detection within IR and color images. The RXD algorithm compares every pixel in the image to the mean of all the pixels. In the most common implementation, a mean, μ, and covariance matrix, τ, are computed using every pixel in the image; the RXD output is the Mahalanobis distance of each pixel from the mean, as shown in the following equation:

$$\boldsymbol{RXD = (x-\mu)\tau'(x-\mu)}$$

Many variants of the RXD have been developed; a good overview of the RXD algorithm can be found in Basener and Messinger reference [9].

This study used the ERDC-developed RXD algorithm. The algorithm classified each pixel as either background clutter or an anomaly target using a background mask, target mask, and blanking mask. After computing the covariance matrix, a background mean and a target mean were computed using the pixels labeled as background or target as determined by filtering using the respective mask values. These two estimations (covariance and mask-filtered pixel classifications) are combined using a maximum likelihood ratio test. The final RXD results are then run through a false alarm mitigation (FAM) algorithm [2]. Results of the RXD algorithm for positively detected anomalies can be seen in figure 3 for two different camera configurations.

For this study, the RXD mask values were fixed irrespective of the sensor viewing geometry and the RXD algorithm was not run on any training data to optimize the mask values. While this is not considered 'best practice' for image-based anomaly detection, the optimization of the RXD algorithm was outside the scope of this work. The untrained algorithm was sufficient to provide a baseline

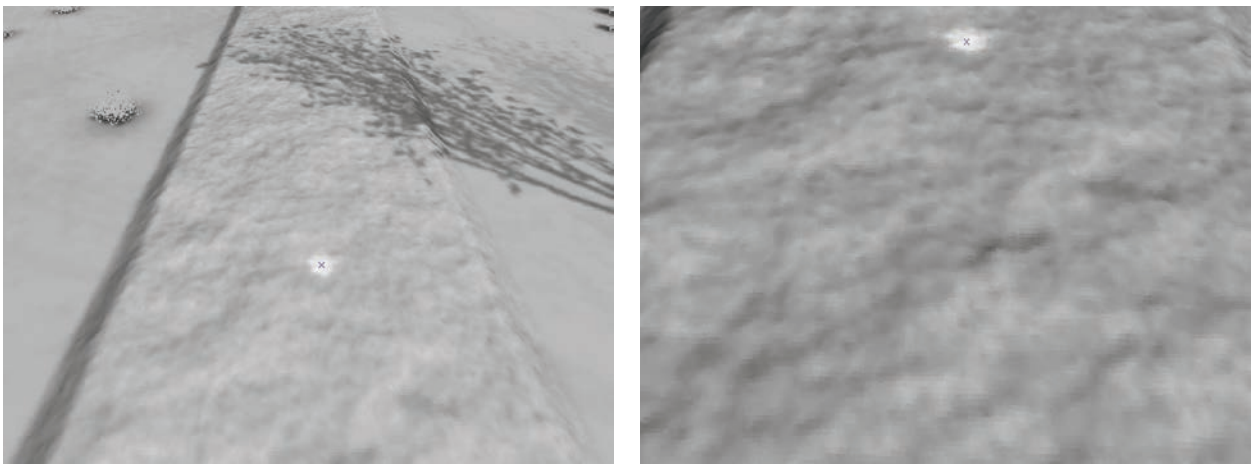

Figure 3: Two images from the thermal camera simulation. The 'x' indicates that the RXD algorithm identified the target region

performance estimate to explore the vehicle design space.

Analysis

The standoff distance for each camera configuration was calculated based on the height and opening angle of the lens. Then, for each configuration, the number of times the target was detected by the RXD algorithm was divided by the number of frames for which the target was in view, as determined by a human analyst. Following this process, a standoff distance and a probability of detection was calculated for each configuration. The resulting plots are shown in figure 4.

The two camera configurations are distinguished by red and blue lines in figure 4, while a fit to the data is shown

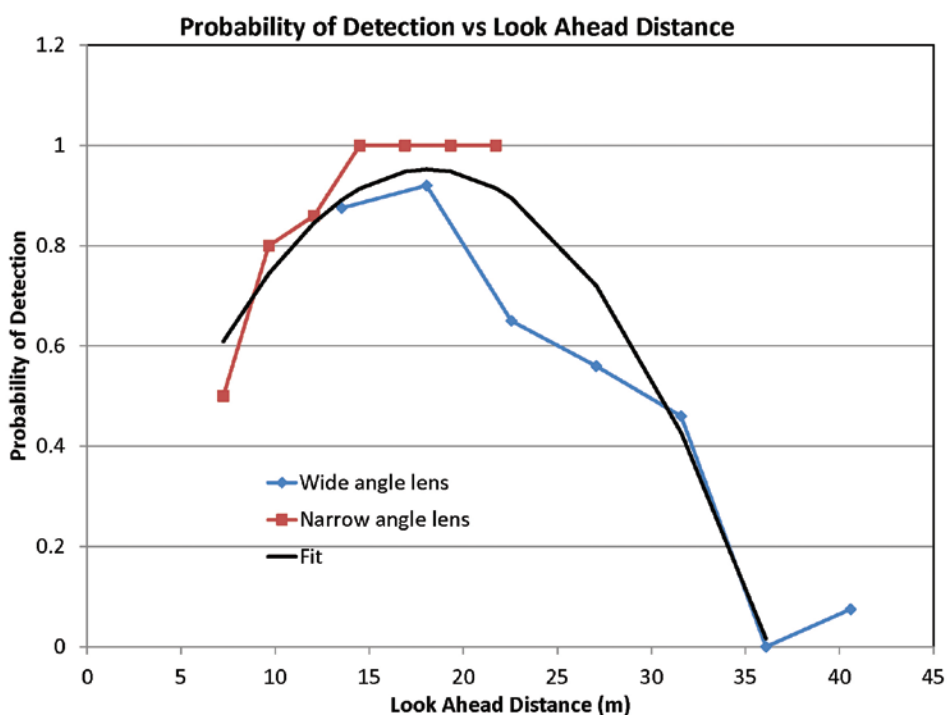

Figure 4: Result of analysis. The black curve is a fit to the combined data set.
The equation of the fit is $P_d = -0.0029x^2 + 0.1051x$ where P_d is the probability of detection and x is the standoff distance.

in black. The analysis reveals that the highest probability of detection occurs at standoff distances of approximately 18 meters. At distances shorter than 18 meters, there is not enough terrain in the image to get an adequate representation of the background for the RXD algorithm. For distances greater than 18 meters, there were not enough pixels on target to reliably detect the anomaly.

In an ideal case, a standoff distance of 18 meters would limit speed to around 19 m/s or about 43 miles per hour. If this particular sensor modality were used to detect shallow buried threats, then the vehicle would need to travel less than 43 miles per hour to give the operator enough time to stop if a potential target was detected.

Discussion

It is important to note that this analysis is constrained by a limited sample size. The analysis was performed for a specific vehicle-sensor pairing for one environmental condition at a single location. To support real acquisition related decisions, a more comprehensive set of simulated tests would needed. However, the work presented in this paper shows that it is possible to conduct these experiments in a controlled virtual environment. The cost and time savings of using a virtual analysis represents an advantage over field trials as well as the ability to precisely control environmental conditions for the simulation.

While the digital terrain used for this analysis represented a geo-specific location, it is possible to conduct simulations on "geo-typical" terrain, or terrain that represents a particular climate or terrain without being linked to a specific location. These geo-typical scenes offer several advantages over the geo-specific terrain used in this work. First, geo-typical terrains are faster and more economical to generate because they do not require field data collection. Secondly, it is possible to incrementally vary environmental variables in the terrain design to create a set of similar terrains that have key differences that may impact the analysis. For example, geo-specific terrains which are identical except for the surface roughness of the road could be created as a set spanning a desired range of surface roughness values, allowing a detailed analysis to be conducted for sensitivity to the particular environmental parameter while controlling the other parameters.

Conclusion

VANE, a high-fidelity physics-based simulation tool, was used to simulate a vehicle-mounted IR sensor and determine the optimal standoff distance for the sensor to detect shallow buried threats which appeared as temperature anomalies in the IR images. Surface and subsurface temperatures were calculated using the GEOTACS-CTB. The analysis showed that, for the particular environmental conditions under consideration, the optimal standoff distance was about 18 meters. For a typical vehicle under ideal conditions, this corresponds to a maximum speed of about 43 miles per hour to ensure a safe stopping distance in the event of a detected target.

This paper has showed how physics-based simulation can be effectively used to quantify the parametric relationships between vehicle and sensor characteristics. These relationships could be used to inform trade-space tools for making optimization decisions.

Acknowledgments

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U.S. Army Sensors Life Cycle Acquisition with Modeling and Simulation

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Abstract

THE U.S. ARMY'S NIGHT VISION AND ELECTRONIC SENSORS DIRECTORATE (NVESD) MODELING AND SIMULATION DIVISION (MSD) USES MODELS AND SIMULATIONS (M&S) TO IMPROVE SYSTEMS ACQUISITION PROCESSES BY REDUCING TIME, RISK AND RESOURCES WHILE INCREASING UTILITY AND SUPPORTABILITY. THE MSD PROVIDES U.S. GOVERNMENT-OWNED M&S TO U.S. ARMY PROGRAM EXECUTIVE OFFICES/PROJECT AND PRODUCT MANAGERS (PEO/PMS), SUPPORTING ACQUISITION PROGRAMS ACROSS THEIR LIFECYCLE. THE MSD SUPPORTS SENSOR ANALYSIS, DEVELOPMENT, EXPERIMENTATION, TESTING, FIELDING, TRAINING AND OPERATIONS BY PROVIDING SENSOR PERFORMANCE MODELING; REFINING MODELS THROUGH FIELD AND LABORATORY MEASUREMENTS OF DEVELOPED SENSORS; AND PROVIDING SENSORS M&S TO EXPERIMENTS, TESTS AND TRAINING.

THE MSD SUPPORTS THE FULL ACQUISITION LIFE-CYCLE OF SEVERAL SENSOR PROGRAMS. THE MSD DEVELOPS AND PROVIDES MODELED SENSOR PERFORMANCE CHARACTERISTICS AS SPECIFICATIONS TO INDUSTRY FOR DEVELOPMENT, AND TO SUPPORT CONCEPT EXPERIMENTS AND CAPABILITIES ASSESSMENTS. THE MSD USES SIMULATIONS TO SUPPORT MATERIAL SOLUTION ANALYSES (MSA) AND DESIGN STUDIES TO IDENTIFY THE PREFERRED SOLUTIONS WITHIN FUTURE SENSOR SYSTEMS. THE MSD PROVIDES SIMULATIONS AND DATA COLLECTION TO SUPPORT BUSINESS CASE REVIEWS (BCR) LEADING TO MILESTONE B DECISIONS ON WHETHER TO PROCEED WITH FURTHER DEVELOPMENT OF NEW SENSOR SYSTEMS. MSD'S M&S SUPPORTS TRADE-OFF ANALYSES, SYSTEM PERFORMANCE TESTS FOR SPECIFICATION ADHERENCE, AND TESTS OF INDIVIDUAL SENSOR SYSTEMS AND THEIR SYSTEMS INTEGRATION. THE SENSOR PERFORMANCE MODELS ARE REFINED AS INDUSTRY PROTOTYPES AND SYSTEMS ARE TESTED, AND FURTHER USED IN MSD SIMULATIONS. MSD DEVELOPS NEW EQUIPMENT TRAINING (NET) SIMULATION SYSTEMS AND DESKTOP TRAINERS, AND TRANSITIONS THEM TO TRAINING PROGRAMS OF INSTRUCTION. THE MSD RE-USES ITS M&S ACROSS SENSOR PMS, AND FOR OTHER PMS USING SENSOR TECHNOLOGIES WITHIN THEIR SYSTEMS.

The U.S. Army uses models and simulations (M&S) to contribute to the success of Army missions and systems acquisition processes by reducing time, risk and resources while increasing utility and supportability. According to

Army Regulation AR 70-1, Project and Product Managers (PMs) should use M&S "throughout the system acquisition process in a robust, collaborative manner to address system development..." PMs are required to "incorporate M&S in their acquisition strategies, as prudent, to reduce cost and accelerate decision cycles in systems engineering and test and evaluation activities throughout the acquisition process [1]."

The U.S. Army's Night Vision and Electronic Sensors Directorate (NVESD) Modeling and Simulation Division (MSD) provides sensors acquisition engineering and analytical support and an extensive set of Government-owned M&S to several Army Program Executive Offices/Project and Program Managers (PEO/PMs), supporting numerous Army acquisition programs across their lifecycle. The MSD is organized to support sensor analysis, development, experimentation, testing, fielding, training and operations by: 1) providing sensor performance modeling, 2) refining models through field and laboratory measurements of developed sensors, and 3) developing models and simulations using physics-based algorithms of actual sensor performance or platforms. The M&S includes electro-optic, infrared, acoustic, magnetic, seismic, synthetic aperture and ground penetrating radar sensors as well as certain munition effects related to the sensors' capabilities.

To support sensor analysis and development, the MSD develops and provides the Night Vision Integrated Performance Model (NV-IPM). This integrated set of sensor performance characteristics is based on physics research performed by the laboratory. The NV-IPM is a systems engineering tool that enables model-based engineering with a simple interface for trade studies. The sensor characteristics and modeled parameters can be provided as specifications to industry for actual development. Figure 1 offers an example of the NV-IPM interface showing varied modeled sensor parameters and characteristics. The integrated model allows for a common baseline of performance specifications and scene conditions to enable prototype sensor systems development by industry. The NVESD validated physics models allow the laboratory to compare many diverse sensor systems based on current research and/or potential development.

Sensor performance models are used both for data collection and analysis and to support concept experiments and

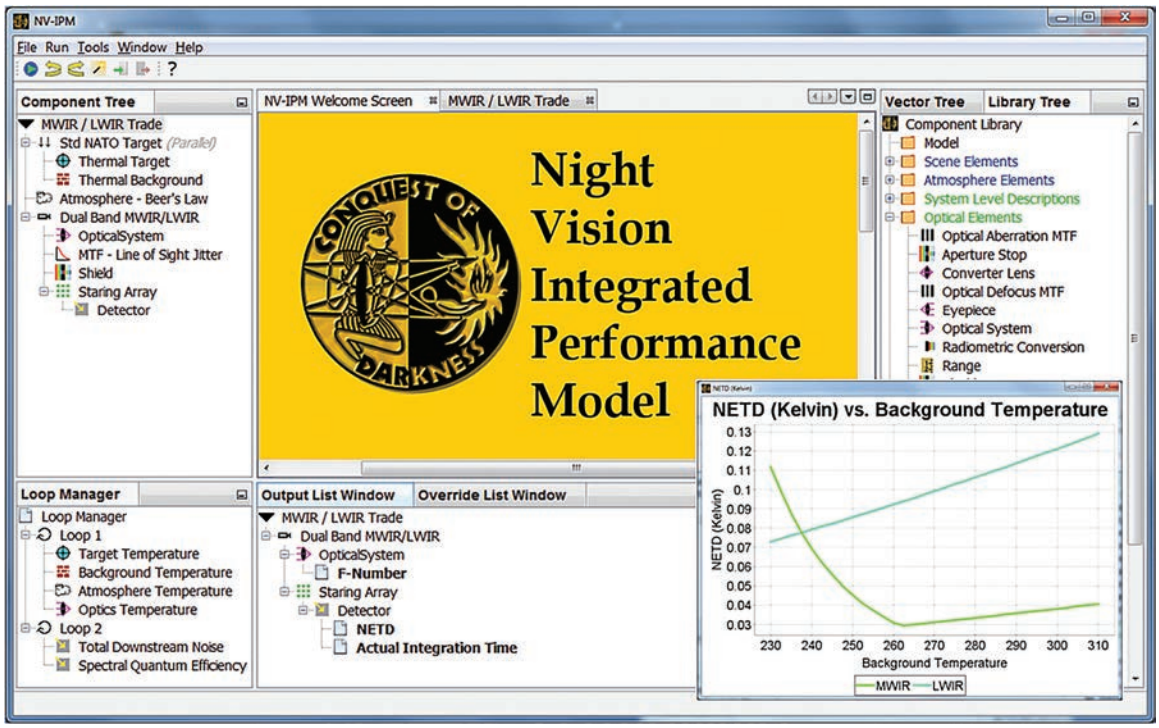

Figure 1: Example NV-IPM Interface

capabilities assessments. For example, the MSD used a virtual simulation to measure and determine the overall effectiveness of a virtual pointer (VP) targeting system, ultraviolet (UV) target marking system, and a system combining the two technologies during the Material Solution Analysis (MSA) phase of the projects. The simulation also included a Soldier (human-in-the-loop) subjective survey that helped to identify the preferred solutions for pointer shapes, sizes, colors, and reticle patterns within future optics systems. This subjective data was analyzed along with the sensor performance data to determine what factors led to the best target acquisition and identification times using the various targeting technologies. An example of a future optics design experiment is shown in figure 2.

Figure 2: Future Optics Design Experiment Example

To support the Milestone B decision for the future Family of Weapons Sights (FWS) capabilities, the MSD provided simulations support to Product Manager (PM) Soldier Maneuver Sensors (SMS), under Project Manager Soldier Sensors and Lasers (PM SSL). The MSD planned, executed, and analyzed a series of data collection simulations comparing the FWS to the current Thermal Weapon Sights (TWS) capabilities. The data collected was used to support a business case review (BCR) that led to the decision to proceed with further development of the new sensor system.

Following the analyses, MSD planned and executed a FWS-I User-Interface (UI) and Remote Switch design study. The virtual simulations allowed Soldiers to provide subjective feedback on components of the UI based on human-in-the-loop exercises. This study analyzed items such as the best rapid target acquisition (RTA) reticle attributes, response times, and the preferred menuing and overlays options for the system. Trends were identified to determine what features of the FWS-I UI should be considered as requirements for the system and were incorporated into a report to PM SMS. The MSD continues to support FWS analyses and tests as development proceeds.

Sensor performance models and simulations are continually improved as industry prototypes and systems are tested during field and bench tests. The refined M&S are used for sensor testing, fielding, training and operations. The Program Manager Close Combat System (PM CCS) Scorpion system used a verified and validated MSD physics-based model to provide munitions effectiveness and system performance estimates prior to live testing. MSD created a real time casualty assessment (RTCA) tool that intercepted a munition launch message, carried out the RTCA, and notified the human operator of whether their target had been killed or not. By using these M&S capabilities, PM CCS was able to determine weaknesses of their detection and fusion algorithms and suggest corrections to the prime contractor before the problems were exposed in live testing. PM CCS was able to realize cost and schedule efficiencies by planning risk mitigation in advance and eliminating the need for expensive and repetitious live field testing requiring the acquisition of expensive live targets with robotic controls.

The MSD developed and continues to develop New Equipment Training (NET) simulations solutions for other systems under PM SSL to support fielding and deployment training. These are software based virtual training solutions for over twenty PM SMS and PM Soldier Precision

Targeting Devices (SPTD) sensors including the TWS, Enhanced Night Vision Goggle (ENVG), PVS-14 Image Intensifier (I2), Lightweight Laser Designator Rangefinder (LLDR), various Laser Target Locators (LTL) and several other sensors. The MSD modeled the physical devices and characterized each of the sensor systems in the Night Vision Image Generator (NVIG) and an associated hardware emulator for use in future training systems. For the TWS, MSD created an interactive multi-media instruction sensor trainer to support NET (see figure3). The trainer incorporates 3D simulation scenarios, using appropriate sensor visuals and models of the physical devices, to train TWS tactics, techniques, and procedures.

The MSD supported the full acquisition life-cycle of the Long-Range Advanced Scout Surveillance System (LRAS3) (see figure 4), which was initially developed by NVESD to fulfill a requirement for PM Forward Looking Infrared (PM FLIR). During the research and development process, MSD developed runtime visual models within its simulations of the different systems' conceptual capabilities to support a trade-off analysis of the system prior to the development of any prototype components. The second generation FLIR was chosen to meet the LRAS3 program's requirements. As a follow-on effort, NVESD used M&S tools to develop simulation models, within a sensor simulator, to test the system performance in a laboratory environment for specification adherence. This same simulator, and its underlying models, was then further developed for use with the NET simulation system. All functionality of the physical system was incorporated into the simulation. The total savings to PM FLIR by reusing the Government models were several millions of dollars. These savings were passed on to the LRAS3 program, which allowed the program to develop two sets of mobile training environments that support both operator and maintenance training. To date, the LRAS3 NET teams have used a combination of classroom instruction, simulator training and hands-on training to train over 2000 soldiers on the LRAS3 system. In addition to the cost savings, using the simulator has increased the amount of system training time from approximately thirty minutes per soldier on the actual system to over eight hours using the simulator. As the NET is transitioning to sustained schoolhouse training, the Government Furnished Equipment (GFE) training and maintenance simulators are being transitioned to Fort Lee,

Figure 3: PEO Soldier Sensor Trainer

VA, and to Fort Benning, GA, to be incorporated into their training programs of instruction.

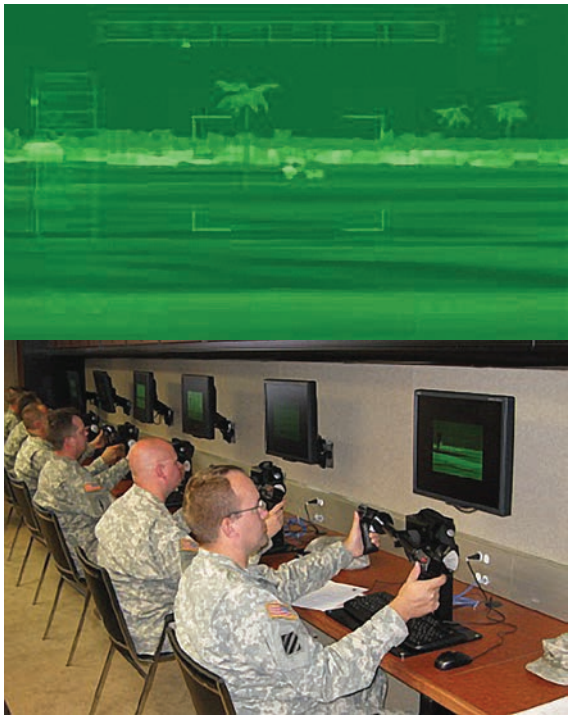

Figure 4: Long-Range Advanced Scout Surveillance System (LRAS3) Trainer

In support of Rapid Fielding Initiatives and subsequent program development of base defense sensor systems, the MSD has developed visual, acoustic and other sensor models that replicate all current sensors and those under consideration for the Base Expeditionary Targeting and Surveillance System–Combined (BETSS-C). These models were used for test development of the individual BETSS-C sensors and their integration into the system. The BETSS-C sensor models were adapted to desk-top training simulations and are used by PM Night Vision Reconnaissance Surveillance Targeting and Acquisition (PM NV RSTA) for NET to deploying units. Figure 5 shows the actual laboratory and figure 6 provides an example of the BETSS-C system simulation view. The models are also being used for testing of the Sensor Ground Station (SGS). The SGS is a common ground station for the BETSS-C system. In addition, the models continue to be used for testing new SGS software and BETSS-C capabilities in live field events in support of Program Executive Office Intelligence Electronic Warfare and Sensors (PEO IEW&S). The use of these MSD M&S models and tools has been critical to BETSS-C employment in Theater as the new sensor systems and SGS are unavailable for home station training. The MSD has provided M&S solutions throughout BETSS-C development and acquisition processes.

Figure 5: BETSS-C Sensors Integration Laboratory

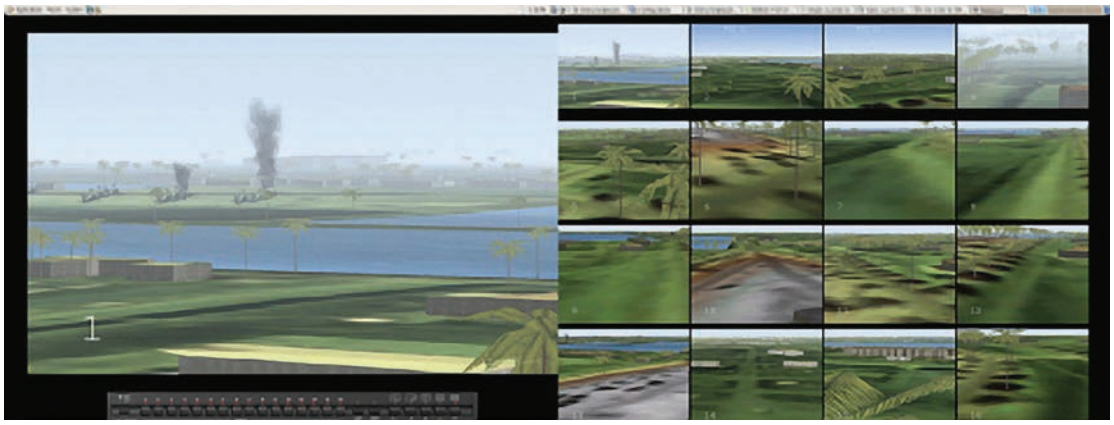

Figure 6: BETSS-C System Simulated View

The NVESD MSD continues to provide M&S support to sensor PMs, and to other PMs using sensor technologies in their systems. The MSD offers Government-owned M&S models, algorithms, simulations and simulator solutions to improve development and realistic training for electro-optic, infrared, acoustic, magnetic, seismic, and ground penetrating radar systems.

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Acronyms

BETSS-C	Base Expeditionary Targeting and Surveillance System–Combined
BCR	Business Case Review
ENVG	Enhanced Night Vision Goggle (ENVG)
FLIR	Forward Looking Infrared
FWS	Family of Weapons Sights
FWS-I	Family of Weapons Sights - Individual
I2	Image Intensifier
IEW&S	Intelligence Electronic Warfare and Sensors
IMCOM	U.S. Army Installation Management Command
LLDR	Lightweight Laser Designator Rangefinder
LRAS3	Long-Range Advanced Scout Surveillance System
LTL	Laser Target Locators
LVC	Live-Virtual-Constructive
M&S	Models and Simulations
MSA	Material Solution Analyses / Analysis
MSD	Modeling and Simulation Division
MTC	Mission Training Complex
NET	New Equipment Training
NV RSTA	Night Vision Reconnaissance Surveillance Targeting and Acquisition
NVESD	U.S. Army's Night Vision and Electronic Sensors Directorate
NVIG	Night Vision Image Generator
NV-IPM	Night Vision Integrated Performance Model
PEO	Program Executive Office
PM CCS	Program Manager Close Combat System
PM SSL	Project Manager Soldier Sensors and Lasers
PM(s)	Program, Project and/or Product Manager(s)
RTA	Rapid Target Acquisition
RTCA	Real Time Casualty Assessment
SGS	Sensor Ground Station
SIMCI	Simulation to Mission Command Interoperability
SISO	Simulation Interoperability Standards Organization
SMS	Soldier Maneuver Sensors
SPTD	Soldier Precision Targeting Devices
SWG	Senior Working Group
TWS	Thermal Weapon Sights
UI	User Interface
UV	Ultraviolet
VP	Virtual Pointer

Authors' Biographies

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Ms. Susan Harkrider is the Deputy Director of the Modeling and Simulation Division at the CERDEC Night Vision and Electronic Sensors Directorate. She has over 20 years experience supporting modeling and simulation, training and systems engineering efforts for the DoD. She has served on the Simulation Interoperability Standards Organization (SISO) Executive Committee and Standards Activity Committee. Ms. Harkrider is currently the chairperson of the RDECOM M&S Senior Working Group (SWG), which facilitates collaboration of M&S efforts between RDECOM laboratories in support of PEOs and PMs. She holds a BSE and MSE from the University of Central Florida.

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Mr. Darran Anderson is a Senior Program Manager for Trideum Corporation, a Project Management Professional and retired U.S. Army officer. He has over 20 years experience supporting modeling and simulation, training and experimentation for the DoD. He served as a Simulations Operations officer at Fort Hood and in the Pentagon Army G-3/5/7 Training. He has overseen simulations tests, experiments, training exercises and mission rehearsals; coordinated Live-Virtual-Constructive (LVC) architecture and systems development; managed strategic policies and resources for simulations and the manning and construction of related simulations facilities; and managed programs overseeing Mission Training Complexes (MTC). Mr. Anderson now works at the U.S. Army Night Vision and Electronic Sensors Directorate (NVESD), Modeling and Simulations (M&S) Division. He supports program management, user coordination and integration of the division's Night Vision Toolset simulations applications, and sensors and simulations operations within the division's Sensor Integration Laboratory.

Mr. Andrew Krug

Mr. Andrew Krug is a Project Management Professional, simulations and information technology specialist with more than fifteen years experience in managing day-to-day operations of projects, planning strategic objectives, networks and architecture design, simulations design and integration, creating technical documents, and providing daily programmatic support. Mr. Krug currently works at the U.S. Army Night Vision and Electronic Sensors Directorate (NVESD), Modeling and Simulations (M&S) Division. His experience includes planning, integrating, and executing live-virtual-constructive (LVC) sensor training, experiments and concept development simulations. He manages sensors simulations design and testing used for research and development with a focus on infared sensors and active lasers.

Application of Live-Virtual-Constructive Environments for System-of-Systems Analysis

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Abstract

LIVE-VIRTUAL-CONSTRUCTIVE (LVC) SIMULATION ENVIRONMENTS ARE WELL ESTABLISHED AS TRAINING AND TESTING SOLUTIONS. ALTHOUGH THE DOD HAS THE REQUIREMENT TO PERFORM DETAILED ANALYSIS OF COMPLEX SYSTEMS OF SYSTEMS (SOS) THAT COULD BE REPRESENTED BY LVC SIMULATIONS, SUCH AN APPROACH IS NOT GENERALLY ADOPTED. IN THIS PAPER, WE ADDRESS THE COMPLEXITY OF SOS ANALYSIS, COMPARE AND CONTRAST THE MODELING AND SIMULATION (M&S) REQUIREMENTS FOR SOS ANALYSIS VS. TRAINING AND TESTING, AND USE THE RESULTS TO IDENTIFY THE BENEFITS AND DRAWBACKS OF APPLYING LVC TO SOS ANALYSIS. SPECIFIC RECOMMENDATIONS FOR ADDRESSING THE BENEFIT/DRAWBACK ANALYSIS ARE PROVIDED AT THE END OF THIS PAPER.

System of Systems Complexity

Systems of Systems (SoS) analysis is most often encountered during the systems engineering process within the technology development and engineering phases of major acquisition programs. The vast majority of these analyses are performed by engineers of various disciplines using monolithic constructive simulations that model multiple systems and the interactions among those systems. The use of multiple simulations, run simultaneously and interoperating in a distributed environment is not common practice. The results of individual, standalone simulations, usually referred to as engineering-level simulations, are typically used in conjunction with other engineering level simulations and engagement simulations in an analysis pyramid as illustrated in figure 1 [1].

Rather, than using distributed simulation, analysts have several different approaches for SoS analysis. One approach has been to use lower-resolution mission-level models to characterize the full SoS operational environment. In some cases, the lower-resolution nature of these models has been ameliorated by substituting higher-resolution tabular data tables for the lower-resolution "cookie cutter" individual system representations, or using this higher-resolution data to verify the accuracy of the lower-resolution representations. In other cases, the analysts have used multiple standalone models to examine different parts of the overall problem, and use their best engineering judgment to combine the pieces into an assessment of full SoS performance. In still other cases, analysts have attacked the SoS issue in stages, using multiple standalone models/simulations in a serial

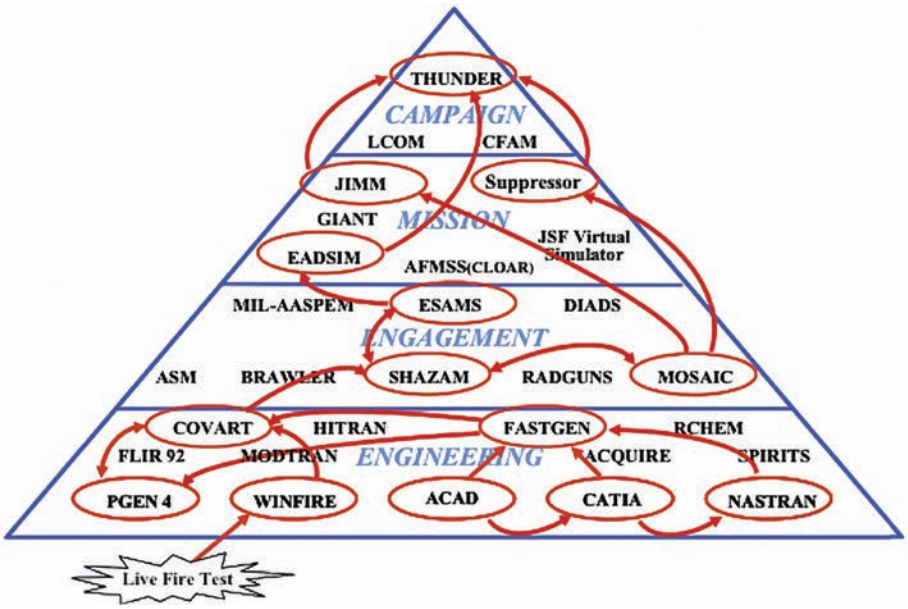

Figure 1: Example Analysis Pyramid

fashion, manually applying the output of one model/simulation to the input of another. All of these methods have various advantages and disadvantages. However, none of these methods really support a fully integrated assessment of all aspects of SoS performance.

High-level operational needs generally drive the requirements for a system. Needs change over time as strategic or tactical military objectives and perceived threats to meeting those objectives change. New systems or modifications to existing systems are proposed to address those changing needs. However, while individual systems can contribute to defined military goals, it is the overall capability created by the coherent integration of many systems along with an appropriate concept of operations that really addresses the core operational requirements. For instance, an unmanned aircraft system (UAS) includes a variety of sensors, communications equipment, and other payload elements that must work in unison to provide the desired full system capability. Thus, in one sense, the UAS is itself a SoS. However, the UAS must also interact with other manned aircraft and joint, theater or national assets to fully support the military and/or homeland security missions for which it was designed. Modeling is defined as "Application of a standard, rigorous, structured methodology to create and validate a physical, mathematical, or otherwise logical representation of a system, entity, phenomenon, or process [2]." This definition makes it clear that modeling is a process that builds a useful representation. The scope and complexity of a model vary widely as a function of the intended use. No affordable model can represent the system, entity, phenomenon, or process perfectly, so alignment between the representation and intended use is critical.

At the individual subsystem level, constructive standalone modeling and simulation (M&S) tools are often used to support most acquisition functions, such as subsystem-level design and development. The problem is sufficiently constrained that a simple tool can handle the intended use. Subsystem components that have not yet been designed cannot be understood at the level of detail that is known after units have been produced and field-tested. Through the course of subsystem development, testing methods add to the knowledge derived from M&S for subsystem-level requirements verification purposes, and also to provide evidence of credibility for the M&S tools that augment the testing.

However, verifying that the fully integrated SoS meets mission requirements in defined tactical or operational situations represents a completely different intended use. Exhaustive testing is prohibitively expensive, even in circumstances where individual systems are all extant, at least in prototype form. Standalone M&S tools do not represent the complexity of the full mission space with a degree of fidelity adequate to answer the questions posed. Other methods and tools must be employed. Working from the intended use to narrow evaluation criteria and test cases can produce an acceptable M&S solution, but adequate representation of SoS complexity often comes at the expense of generality.

Current LVC Environment Applications

In the test and training domains, combinations of Live-Virtual-Constructive (LVC) M&S assets are regularly used to address SoS issues. Using modern distributed simulation technology, simulations of individual SoS components can be linked together to create a very powerful real-time SoS representation. This requires integrating dozens or hundreds of heterogeneous systems potentially developed with different objectives, assumptions, and software engineering baselines, i.e., a significant engineering undertaking.

In the training domain, the Services frequently mix LVC simulated forces as a means for creating a realistic common operational picture for a student operator. In the test world, a similar mix of LVC assets is frequently used to provide an appropriate stimulus for a system under test. In general, the test and training communities depend heavily on the availability of a supporting, integrated set of LVC M&S assets to accomplish core functions.

The late development phases at which training or testing occur have enabled these M&S approaches to be effective. Programs have run for years, and the resulting subsystem has been thoroughly examined. All the possible designs and ideas have been distilled, at significant expense, to a single specific implementation. Test data on the implemented subsystem is available and the operational context for its operation is documented. By combining all these facts, a specific simulation federation can match accurately the pre-defined test or training scenarios. Connecting the simulation to a real-world range with actual human operators provides added realism.

Analysis Requirements

In the analysis domain, the situation is noticeably different. Analysis applications typically involve the examination of a very large tradespace of conceptual options, which must be evaluated to identify the most promising system concepts to take forward into design. Large uncertainties in how the concept might be implemented and the sheer volume of options tend to rule out the sort of constrained, well-defined M&S solutions that training and testing have the luxury of employing. Also, there are usually many stochastic factors that must be accounted for in the design of experiments, and achieving statistical significance requires a large number of trials. Typically, the time available to achieve the analytic result, in combination with these factors, necessitates use of models and simulations that run much faster than real time. For that reason, only the constructive aspects of LVC have been applied to the analysis domain in the past. However, if the SoS analysis requires consideration of human factors, it may require virtual and even live M&S assets.

It is unclear that these pitfalls are the primary reason that the use of individual, constructive simulations with manual data passing is the predominant model. A more likely explanation is that the engineers use these models because they are familiar with them, and have confidence in the results of the models, e.g., they pass face validation. The engineers view these constructive simulations as sufficient for their purposes, unburdened by the need to involve the live operators needed for virtual and live simulations, and the effort involved for the integration of multiple simulations into a distributed environment. Repeatability of results (determinism) is usually the goal for these analyses. Introducing human operators almost always removes that repeatability, and uncertainty about latencies and potential data loss in best-effort distributed simulation environments has the same effect. Add this to the learning curve necessary to utilize distributed simulation, and it is understandable why most analysts rely on the individual constructive models with which they are most familiar.

Applicability of LVC to SoS Analysis

Incorporating distributed simulation into the SoS analysis approaches described above could bring the benefits of integrating insight from multiple models and higher-resolution modeling than would be otherwise practical for SoS analysis. However, the federation could also bring the disadvantages of additional complexity and reduced robustness as compared to a single M&S tool. Furthermore, verifying the credibility of modeling results may be more difficult due to semantic differences between the simulations' conceptual models and abstractions. An extensive Verification and Validation (V&V) effort could at least partially address these disadvantages. However, the more that must be invested in an analysis solution before any

answers are produced, the fewer analysis problems the allocated schedule and cost can produce.

The clear advantage of using distributed simulations is the ability to combine models that represent individual systems very well. By combining them in a distributed environment, analysts can use the "best of breed" models for each simulation. The assumption is that the difference between the simulations in these distributed environments are the system or set of systems they model, not the way in which they model effects or interactions. For this approach to work, each system must be modeled at a comparable level of detail, make analogous abstraction decisions, and generally have compatible conceptual models. Note that all of these distinctions are generally understood in the abstract, but are nearly impossible to quantify within the current state of the art. In engagement simulations, mismatches of these types usually emerge as "fair fight" issues. For example, if one simulation considers terrain masking, and another does not, the simulations are likely to differ in their understanding of who can sense and shoot whom. These issues are just as important in SoS evaluations, where the issue becomes one of substantive interoperability [3]. As has been observed, distributed simulation architectures such as the High Level Architecture (HLA) [4] can ensure technical interoperability (that simulations can exchange data), but not substantive interoperability unless their conceptual models are aligned. The problems described in this paragraph are generally consolidated under the label of composability.

For analysts to become more comfortable with distributed simulation, the operation of a federation of simulations must be as quick and straightforward as standalone model operation. This means that operation over wide area networks (WAN) using legacy architectures is less likely to be viable, due to the high degree of coordination that is necessary across multiple distributed facilities. This situation argues for either a service oriented architecture (SOA) solution that is always on and requires little to no intervention, or a completely localized solution where all simulation assets are under the direct control of the analyst. However, neither of these solutions can readily incorporate live and virtual assets beyond the analyst. And establishing multiple local environments for the use of a small set of analysts would be costly.

Beyond the advantages of integrating best of breed simulations into distributed simulations, LVC environments get significant fidelity from real-world ranges with actual human operators. These live assets have not traditionally been used in analysis situations because human operators simply cannot perform deterministically enough to hold their performance constant while other parameters vary in the Monte Carlo statistical trials that are usually the basis of analysis. Another limiting constraint would be the availability of trained operators for the systems under analysis and the cost of using them.

Emerging techniques to combine fast-time constructive M&S tools with real-time human-in-the-loop LVC environments have shown promise for addressing some of these limitations [5]. Constructive M&S tools are generally very effective at quickly searching a wide range of independent variables and varying operational conditions to identify deficiencies and limitations in SoS performance. However, representations of human behavior and performance in such models are usually constrained to relatively simplistic rule-based decision logic, largely due to the need to run large numbers of runs with different random number steams. That is, achieving an accurate representation of human behavior in simulation is computationally expensive, and it is not generally practical to incur this cost when employing Monte Carlo analysis techniques to obtain statistically significant results for studies with aggressive analysis schedules. More fidelity can be achieved through the use of real-time human-in-the-loop LVC environments executing selected vignettes representing stressing situations to SoS human operator(s). The data collected on human operator performance/behavior during the LVC executions can be converted into probability distributions that can be sampled by constructive models at runtime to drive their internal decision logic. This allows the analyst to have access to statistically significant results on SoS performance without the prior fidelity limitations on how humans are represented. It also allows the analysts to consider additional operational conditions that could not be explored in the LVC environment due to time and cost constraints.

Without taking variability into account, the analyst cannot know if the observed effects are due to chance or are statistically significant. This principle applies to SoS

analysis when human operators are part of the systems, and is a compelling reason for employing virtual and live simulations for SoS evaluation, expressly because they introduce the type of variability attendant to human involvement that is not always captured through stochastic measures. The inclusion of real operators offers the potential for emergent behavior. In a SoS environment, this is evident when the live operators evolve techniques, tactics, and procedures (TTPs) that are not scripted to take advantage of SoS effects and capabilities. Emergent behavior may also be observed if constructive intelligent agents are used in a constructive environment to model operators. However, an intelligent agent cannot explain the thought process that led to the improved TTP, where a human operator can. Understanding thought processes can lead to further improvements in SoS effects. In the end, that is a key goal of SoS, achieving an effect that is greater than the sum of the parts.

While achieving a composable LVC capability is a significant engineering challenge, it can be achieved and the benefits are manifold. A composable LVC environment enables SoS engineering analysis, requirements validation, distributed integration, incremental test, and end-to-end SoS evaluation, experimentation, and training. In such an environment, system simulations, based on key performance parameters, work together to represent overall SoS capability as requirements are written. Real and simulated systems can plug in, using actual interfaces, to work with other actual or simulated systems to integrate, test, and evaluate as you go. As a result, engineering in the simulation is cheaper and safer, like training in a simulation, because it is quicker to clean up mistakes and reset to try the next good idea.

Analysis of Benefits and Drawbacks

Table 1 synthesizes the benefits and drawbacks of applying LVC to SoS analysis as identified in the preceding sections of this paper.

Table 2 provides an analysis of the relationships between the individual benefits and drawbacks, indicating where they may or may not offset each other. The coloring in the table has the following meaning:

- Green – benefit offsets drawback
- Yellow – offset between the benefit and drawback must be determined on a case by case basis
- Red – drawback offsets benefit
- None – N/A; no relationship between the benefit and drawback

Benefits	Drawbacks
■ Allows reuse of best of breed simulations including system designers' models of future systems ■ Can create a bigger toolbox through the incorporation of different simulations of the same system or phenomenon ■ If SOA were employed, infrastructure (and some integration) challenges could be mitigated ■ Could improve validation against existing standalone simulations by providing true human-driven variability ■ Monte Carlo simulation can be retained within the constructive aspects ■ LVC better represents the reality of the complexity and interaction of a SoS than standalone simulations ■ Enables integration of operational systems	■ Effort/cost to integrate LVC environment ■ Introduction of human-driven variability that could negatively impact validation ■ Validity of composed simulations does not directly follow from the validity of the individual simulations; time and effort to validate ■ Training costs associated with paradigm shift ■ Operating cost

Table 1: Benefits and Drawbacks of Applying LVC to SoS Analysis

Recommendations Based on Analysis of Benefits and Drawbacks

As table 2 illustrates, there is not clear indication of whether LVC will produce a good return on investment for analysis applications. We offer the following recommendations as a roadmap for making such a determination:

1. Identify the set of existing, broadly-used analysis simulations
2. Create an analysis-specific conceptual modeling framework
   a. Map existing analysis capabilities to the conceptual modeling framework
   b. Identify gaps in the conceptual modeling framework and other existing simulations that may fill the gaps
3. Determine the interoperability capabilities of existing analysis simulations
   a. Assess these interoperability capabilities against potential interoperability architectures
4. Determine feasibility of defining metadata standard(s) to support discovery and composition
5. Establish metrics for interoperability, e.g., technical and substantive interoperability, and evaluate the extent to which existing analysis simulations meet them
6. Perform cost/benefit analysis of wrapping or migrating other existing simulations (gap fillers) to an architecture requiring less direct staff support, e.g., SOA

The results of this analysis will not only provide a qualitative and quantitative assessment of the feasibility of developing a composable LVC environment specific to the requirements of SoS analysis, but it will also provide the outline for an implementation plan.

Drawbacks Benefits	Integration Effort / Cost	Human-Driven Variability	Validity of Composed Simulations	Training Cost	Operating Cost
Best of breed / higher resolution	The increased effort may be ameliorated by the benefit of more accurate models.	N/A	Whether the value of more detailed models offsets the challenges of validation of the composed simulations would have to be determined on a case-by-case basis.	The costs of training analysts to use a new suite of tools would be non-recurring.	Whether the value of more detailed models offsets the cost of additional staff to operate the simulations would have to be determined on a case-by-case basis.
Bigger toolbox	Having access to a wider range of tools is a key benefit of using an LVC interoperability architecture.	A bigger toolbox with multiple simulations would allow the analyst to make different choices when human-driven variability is less tolerable, e.g., choosing a constructive simulation rather than a live human.	Whether the ability to choose different models offsets the challenges of validation of the composed simulations would have to be determined on a case-by-case basis.	The costs of training analysts to use additional tools would be non-recurring and may be offset by the value of the additional functionality.	Whether the ability to choose different models offsets the cost of additional staff to operate the simulations would have to be determined on a case-by-case basis, but one of the model choice criteria could be operating cost.

Table 2: Relationships Between Individual Benefits and Drawbacks

Drawbacks Benefits	Integration Effort / Cost	Human-Driven Variability	Validity of Composed Simulations	Training Cost	Operating Cost
SOA	SOA could lower integrations cost.	N/A	N/A	A consistent interface to SOA-based models allows new models to be integrated without incurring the costs associated with training analysts to use a new suite of tools.	The cost of operating a SOA is offset by establishing governance rules that simplify connection and communication. Operating costs can be amortized across multiple users.
Improve validation of existing models	N/A	Whether these validity considerations offset each other would have to be determined on a case-by-case basis.	Improving the validation of existing simulations improves validity of the composed simulation.	N/A	N/A
Monte Carlo	Retaining the ability to use Monte Carlo in an LVC environment can lower the cost and time to conduct events with that environment, and thus offset the integration.	If repeatability is a critical requirement, then the ability to retain Monte Carlo in an LVC environment offsets this issue.	Whether the ability to continue to use Monte Carlo offsets the challenges of validation of the composed simulations would have to be determined on a case-by-case basis.	There is no additional training cost assuming the Monte Carlo simulation is the one currently used by the analyst.	The retention of Monte Carlo can lower operating cost by reducing some of the need for live operators.
Represent complexity of SoS	The ability to provide a selective-fidelity representation of system and operator effects offsets the cost of integration.	If SoS complexity must be represented, but human variability introduces intolerable uncertainty, then stochastic constructive is the solution.	SoS simulation suffers from validation complexity issues whether LVC is applied or not. However, the introduction of human variability may produce a more valid simulation.	N/A	If SoS complexity representation is a key requirement, the achievement of this representation offsets the additional operating cost.
Integration of operational systems	The increased integration effort may be ameliorated by the benefit of the realism of the operational systems.	Integration of operational systems implies the introduction of human operators and their inherent variability.	Validation is more challenging with the integration of operational system, but may be ameliorated by the value of the realism of operational systems brings to the SoS.	N/A	If operational system realism is a key requirement, the achievement of this realism may offset the additional operating cost.

Table 2: Relationships Between Individual Benefits and Drawbacks

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Authors' Biographies

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Dr. Katherine Morse is a member of the Principal Professional Staff at The Johns Hopkins University Applied Physics Laboratory where she researches technologies for improving distributed simulation. She received her B.S. in mathematics (1982), B.A. in Russian (1983), M.S. in computer science (1986) from the University of Arizona, and M.S. (1995) and Ph.D. (2000) in information & computer science from the University of California, Irvine. Dr. Morse has worked in the computer industry for over 30 years, more than 10 of them contributing to open international standards. She has served in multiple leadership positions in the Simulation Interoperability Standards Organization (SISO). Her Ph.D. dissertation is on dynamic multicast grouping for data distribution management, a field in which she is widely recognized as a foremost expert. She is a member of Phi Beta Kappa, Dobro Slovo, ACM, and a senior member of IEEE. Dr. Morse was the 2007 winner of the IEEE Hans Karlsson Award.

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Mr. Robert Lutz is a principal staff scientist at The Johns Hopkins University Applied Physics Laboratory in Laurel MD. He has over 33 years of experience in the design, implementation, and evaluation of modeling and simulation (M&S) systems for military customers. Currently, he is serving as the Navy's Triton Program M&S lead in the Airspace Integration (AI) area. In this role, Mr. Lutz leads the development and employment of numerous constructive and virtual M&S tools in satisfaction of System-of-Systems (SoS) Safety Case analysis requirements. Mr. Lutz recently led several technical projects under the LVC Architecture Roadmap Implementation (LVCAR-I) effort and leads a number of M&S standards activities within the Simulation Interoperability Standards Organization (SISO). He also serves as the Chairman of the SISO Board of Directors and is a regular guest lecturer in The Johns Hopkins University Whiting School of Engineering.

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Modeling Space Launch Process Delays to Improve Space Vehicle Acquisition Planning

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Abstract

U.S. DEPARTMENT OF DEFENSE (DOD) SPACE ACQUISITION PROGRAMS ALMOST ALWAYS EXPERIENCE SIGNIFICANT SCHEDULE GROWTH, WHICH DRIVES COST GROWTH. EVEN WITH THE ADVENT OF MORE RELIABLE LAUNCH VEHICLES, SCHEDULE DELAYS OFTEN EXCEED THREE YEARS AND HAVE THE IMPLICATION OF REDUCED MILITARY OR NATIONAL SECURITY CAPABILITIES, SIGNIFICANT INCREASES IN COSTS AND OCCASIONALLY PROGRAM CANCELLATIONS. THIS PAPER PROVIDES ACQUISITION PROFESSIONALS INSIGHT INTO THE DOD SPACE LAUNCH PROCESS THROUGH MODELING AND SIMULATION. SEVEN CAUSAL DELAY TYPES ARE IDENTIFIED AND THESE FACTORS ARE ANALYZED TO DRAW CONCLUSIONS ABOUT SCHEDULE GROWTH CONSIDERATIONS. WE DISCUSS THE IMPLICATIONS OF THESE LAUNCH DELAY FACTORS AND MAKE RECOMMENDATIONS FOR THOSE INVOLVED WITH SPACE POLICY, ACQUISITIONS, AND LAUNCH.

Introduction

United States Department of Defense (DoD) space acquisition programs are continually plagued with significant unplanned schedule growth. Cost and schedule for required launch capabilities are determined early in the acquisition process based on requirements. An increase in space launch delay affects not only the individual program, but impacts other space acquisition programs' funding and schedule. The Government Accountability Office (GAO) conducted a study of multiple space programs in 2006 to determine the cause of increased costs to programs. Not surprisingly, the study revealed original schedule estimates were particularly unrealistic and unachievable [1], [2].

In the early 1990's, the United States suffered a series of failures of several satellite launch systems that were intended to support DoD and National Intelligence Community (IC) missions. In total, three Titan IV mishaps resulted in nearly three billion dollars in fiscal losses. Subsequently, the Delta III launch vehicle experienced two failures during commercial launches. In addition to the launch failures, several

in-flight anomalies occurred, casting a shadow of doubt on the nation's ability to guarantee assured access to space [3].

As a result of unacceptable failure rates, the DoD introduced major changes in the risk posture associated with space launch. In August 2008, then Major General Pawlikowski, deputy director of the National Reconnaissance Office (NRO) stated, "In the almost decade since the costly failures of the late 1990's, the Air Force Space and Missile Systems Center (SMC) and the NRO have adopted a *back-to-basics* approach to mission assurance [4]." These changes, while intended to promote mission success and assured access to space, also had the unintended consequence of increasing costs and extending launch schedules.

In order to drive down cost and schedule impacts, the DoD generated a new approach to space launch. Boeing's Delta IV and Lockheed Martin's Atlas V launch vehicles became the crucible of our Nation's space launch capability for large DoD and intelligence community satellites. This approach became known as the Evolved Expendable Launch Vehicle (EELV), and was intended to solve cost and schedule issues via competitive pricing and assured access to space on either of the two launch vehicles [5].

In 2005, Boeing and Lockheed Martin formed the United Launch Alliance (ULA), the organization the DoD currently uses to contract Delta IV and Atlas V launch support [6]. Moreover, the DoD is actively pursuing the possibility of commercial space launch from vendors such as SpaceX, the company that has recently supported multiple resupply missions for the International Space Station.

We focused on data from EELV missions since it is the primary launch capability for the United States DoD and intelligence community. The data was collected from the Launch Information Support Network (LISN) and includes missions from June 2006 through March 2013. This effort included the modification and extension of an existing acquisition process simulation, the Enterprise Requirements and Acquisition Model (ERAM). As part of a broader study of simulating DoD acquisition process improvement, this research analyzed the implications of the space launch process on satellite acquisition schedule. With validated simulation of DoD acquisition, research can be conducted on process improvement through critical path and bottleneck analysis, sensitivity analysis of delays, or Lean and Six Sigma task time modifications.

Background

Acquisition Process Modeling

In 2008, ERAM was developed by Lieutenant Colonel J. Robert Wirthlin in an effort to understand key interactions between the requirements generation (i.e., Joint Capabilities Integration Development System), Funding (i.e., Planning, Programming, Budgeting and Execution), and acquisition program portions of the DoD's acquisition process from post-milestone A through milestone C. Wirthlin's model focused on the schedule implications of the process and interactions associated with each arm of the acquisition process in an effort to identify critical interactions that regularly led to significant schedule delays and proposed process or policy modifications that could be implemented to reduce schedules for acquisition programs. Specifically, Wirthlin focused on such questions as, "Why does the system behave the way that it does... are there changes that can significantly improve the schedule [7]?" Majors Leach and Searle [20] extended ERAM focusing on space system acquisition. Major Montgomery later extended ERAM in 2012 by modeling the rapid acquisition process often used by organizations such executing Joint Urgent Operational Needs (JUONS) [21]. More recent research has used Monte Carlo analysis to examine pre-milestone B and C bottleneck analysis and alternatives (interventions) from the baseline simulation [8], [9]. Extensions to this discrete event simulation for space launch drove this research.

Space Launch Policy and Process

The Air Force Space Command's (AFSPC) launch scheduling process guidance and lower echelon documentation was reviewed to ensure comprehensive understanding of the manifesting processes. The primary document which provided the information necessary to understand these processes was Air Force Instruction (AFI) 10-1211, *Space Launch Operations.* AFI 10-1211 outlines the roles and responsibilities of the Air Force as the DoD Executive Agent for Space. Furthermore, it places the SMC Commander as the sole focal point for certification of all DoD and NRO launch vehicles. Additionally, this document specifies that, "launch schedule execution will be based on national

priorities," and designates AFSPC as the responsible agent for establishing the manifest for all DoD, civil, and commercial missions [10].

The launch manifest process is outlined in AFSPCI10-1213, *Launch Scheduling and Forecasting Procedures* and AFSPC *Long Range Launch Scheduling Process* [11], [12]. These documents discuss the Current Launch Schedule Review Board (CLSRB) process from the initial launch support request through launch for space systems. Specifically, the *Long Range Launch Scheduling Process* outlines the National Launch Forecast (NLF) compilation in the 4-to-11 year future and how it flows into the Space Launch Manifest (SLM), which is a near-term, three-year schedule for launches. The CLSRB is a body of stakeholders convened biannually to certify the next 18 months of the SLM [12]. Air Force Space Command Instruction Guidance Memorandum *AFSPCI10-1213/AFSPCGM1* implements minor changes to the process by creating a series of Launch Commit Reviews (LCRs) to assess risk related to launch vehicle (LV) readiness, space vehicle (SV) readiness, ground/control system readiness, and operations readiness. It further delineates organizational responsibilities for each of these risk assessments, and assesses missions scheduled for the next 18 months [11]. These documents define launch scheduling and the capability of the U.S. launch industry.

Space Launch Assessments

The single most significant document related to evolution of the space launch process over the past 15 years is the *Space Launch Vehicle Broad Area Review* (SLV BAR). The SLV BAR, led by General Larry D. Welch, highlighted several problems with the space launch process which occurred in the 1990's. Specifically, the increase in launch failure rates from one per year over a 12-year period to five failures within 10 months. Mission assurance and quality incidents also raised from 18 incidents in 200 launches to 9 in 51 launches, a 100% increase [3]. The SLV BAR began a period of intense scrutiny related to launch vehicle mission assurance, but the added attention to detail and slower pace yielded strong success rates [13]. RAND Corporation, a nonprofit research and analysis organization intended to improve policy and decision-making, highlighted additional issues with the space launch segment, discussing the ramifications of a reduced commercial launch requirement on the cost and schedule of government launches. These issues ultimately led to the combination of the Delta IV and Atlas V teams forming the United Launch Alliance to preserve the EELV heavy lift capability [14].

The GAO's annual assessments repeatedly highlighted issues with technology, design, and production maturity for the spacecraft. Additional issues included synchronization of space and ground segment activation, changes in prescribed program production rates, software related delays, and fiscal and manning constraints [1], [2].

Methodology and Analysis

A model of the space launch process was developed using Grounded Theory to gain insight into process times, delay causes, and key integration and decision points [14], [22]. Insight was gathered via discussions with subject matter experts (SMEs) from space-community locations throughout the United States. A total of 14 SMEs were utilized, including members from the Air Force Headquarters staff, Air Force Space Command staff, various space vehicle program offices, and the space launch community. Furthermore, SME volunteers ranged from government civilians, military, technical support contractors from Aerospace Corporation, and industry contract partners from the ULA. Most SMEs had 15 or more years in the industry, and some had as many as 30 years experience with the space launch process, including several active and retired senior military leaders. The SME discussions covered the full spectrum of the space launch process to include space launch requirements, budgeting, space vehicle integration, and launch operations.

Delay Types

In addition to qualitative SME input, historical data was collected from the LISN database maintained by the Launch, Ranges and Networks Division of Headquarters Air Force Space Command. Data was collected on all previous EELV missions, which resulted in data availability from June 2006 through March 2013. The final dataset included 33 missions and a record of 389 launch date changes and causes for these changes. Each mission history yielded many Launch Change Request (LCR) data

inputs, ranging from as few as 4 LCRs to as many as 32 LCRs. The team then binned the individual delays found on LISN into the most appropriate category, and separated them by launch vehicle type (Atlas vs. Delta) to allow for statistical analysis.

Using the coding techniques of Grounded Theory, the team was able to discern seven primary categories of delay plaguing the space launch process post-milestone C [15]. The delay categories are described in table 1. Delays either occurred for similar reasons, at similar times within the planned timeline, or were due to common external factors. These categories aided in simplifying the model and provided a venue for later analysis. Most significantly, data coding ensured individual categories fit common and manageable distributions for inclusion into the resulting model.

Atlas and Delta Comparison

SME discussions indicated a potential difference between the space launch timelines associated with Atlas and Delta missions. Specifically, it was believed the Launch Vehicle Long Term, Launch Vehicle Short Term, Re-queuing, and possibly the priority delay categories were dependent upon the launch vehicle type and associated reliability and launch rates. Delays related to the space vehicle, both early and late, as well as weather and miscellaneous delays were expected to be launch vehicle agnostic.

Upon examination of the data shown in table 2, our research team found the delay categories did not appear significantly different based on the launch vehicle type; a direct contradiction to SME expectations. A t-test was completed against the null hypothesis that the Atlas and Delta sample means

Space Launch Delay Categories	
Delay Type	**Description**
Space Vehicle - Early (SV Early) (>18 months)	Delay initiated by the SV program office 18-months or more prior the predicted launch date. These delays typically have little impact on the ability to manifest a specific desired launch date at either Vandenberg AFB (VAFB) or Cape Canaveral Air Force Station (CCAFS).
Space Vehicle - Late (SV Late) (<18 months)	Delay initiated by the SV program office within 18-months of the current predicted launch date. These delays often impact the ability to manifest a desired launch date at either Vandenberg AFB or Cape Canaveral Air Force Station (AFS), depending on manifest density. The SV late delays were often of shorter duration than SV early delays, leading to a separate distribution.
Launch Vehicle - Long Term (LV Long) (>18 months)	Delay initiated by the launch vehicle or associated leadership due to known manufacturing issues, launch separation requirements, or updates to an Initial Launch Capability (ILC) for the specific mission. These delays typically have little impact on the ability to manifest a specific desired launch date at either Vandenberg AFB or Cape Canaveral AFS.
Launch Vehicle - Short Term (LV Short) (<18 months)	Delay initiated by the launch vehicle or associated leadership due to unforeseen issues with the launch vehicle, near-term launch date change requests by the mission integrator, or a launch vehicle anomaly on a previous mission that has a ripple effect on the mission of interest. These delays may impact the ability to manifest a desired launch date at either Vandenberg AFB or Cape Canaveral AFS, depending on manifest density.
Re-queue	Delay or, in seldom cases, acceleration encountered when a program attempts to re-enter the launch manifest after it was removed due to another delay such as SV Early. This occurs more often as the re-entry attempt is closer to the planned launch date, generally within 18 months.
Priority	Delay or acceleration of the launch date due to mission priorities. This occurs when the CLSRB process or senior leadership determines a launch date must slip or in seldom cases move earlier to accommodate mission requirements.
Weather / Miscellaneous (Wx / Misc.)	Delay of relatively short duration caused by weather, launch window refinement, or launch range support issues.

Table 1: Taxonomy of Space Launch Delay Categories

were equal for each factor; all p-values shown do not reject the null hypothesis at a 0.05 level of significance.

Delay Analysis

Based on these results, the data was consolidated into a single EELV grouping for all further analysis, as shown in table 3. This was used to build a process model.

It was also insightful to examine the launch delays from a program perspective, with the contribution of overall delay and occurrence by all seven delay categories shown in table 4. This information can be useful by systems engineers and program managers to baseline their schedules. The delay category appearing to have the most significant impact on a program's schedule is the Space Vehicle–Early delay. The Space Vehicle–Early delay is experienced by the SV program office 18-months or more prior to the predicted launch date. At this point in an acquisition program, significant fixes or changes may be incurred, usually extending schedules due to satellite disassembly, reassembly, test, and analysis involved in the specific resolution. While this delay occurs on average only 1.36 times per program, its overall time is the largest at 4.05 months per delay.

Alternatively, the team hypothesizes that satellite assembly, integration, and test issues occurring late in a program

Atlas Delay Category Statistics (Months)							
	SV-Early	SV-Late	LV-Long	LV-Short	Re-queue	Priority	Wx/Misc
Sample Size	25	83	32	28	31	15	17
Mean	3.77	1.18	1.22	0.50	1.75	1.87	0.14
Std Dev	3.99	2.84	2.62	0.63	2.20	4.73	0.20

Delta Delay Category Statistics (Months)							
	SV-Early	SV-Late	LV-Long	LV-Short	Re-queue	Priority	Wx/Misc
Sample Size	20	24	41	28	24	11	10
Mean	4.40	1.09	1.85	0.62	2.30	2.35	0.24
Std Dev	7.68	1.33	2.35	1.64	2.85	3.26	0.52

	SV-Early	SV-Late	LV-Long	LV-Short	Re-queue	Priority	Wx/Misc
T Statistic	-0.3305	0.2197	-1.0600	-0.3645	-0.7885	-0.3094	-0.5674
P-Value	0.7436	0.8266	0.2932	0.7177	0.4349	0.7597	0.5818

Table 2: Initial Statistics of Launch Delay Categories

Delta Delay Category Statistics (Months)							
	SV-Early	SV-Late	LV-Long	LV-Short	Re-queue	Priority	Wx/Misc
Sample Size	45	107	73	56	55	26	27
Probability of Delay Within Category	0.51	0.73	0.67	0.61	0.67	0.58	0.42
Mean Delay	4.05	1.16	1.57	0.56	1.99	2.07	0.18
Median	3.03	0.49	0.72	0.21	0.82	1.00	0.03
Std Dev	5.85	2.58	2.47	1.23	2.49	4.10	0.35
Min Delay	-3.09	-5.46	-4.05	0.03	-0.30	-4.38	-0.03
Max Delay	35.00	15.33	14.05	8.75	11.18	12.99	1.71

Table 3: Overall Launch Delay Statistics

have a significant time impact due to their frequency of occurrence and *ripple* they induce in the overall launch process. Space Vehicle–Late delays occur on average 3.24 times per program but only incur 1.16 months per delay. More importantly, any delay within 18 months of a planned launch has the potential to induce delays in another delay category, such as Priority or Re-queue. This ripple effect may be largely eliminated if the initial SV delay is eliminated. Additionally, from a systems engineering perspective, unforeseen issues late in a program tend to have much greater impact on cost and schedule than early delays.

As shown in table 5, SV-Early delays contribute the most to the overall delay a program can expect to encounter, at 29.3%. In fact, roughly half of all program delay (49.3%) is encountered due to the SV program itself, while the other half is contributed by the launch vehicle or process. Additionally, it could be argued the Re-queue delay is in some cases due to a late SV program delay, hence increasing delay contributed by the SV program.

Model Development

The decision was made to model each of the seven delay categories in series using a double loop for each delay type. The logic used is illustrated in figure 1. The seven individual delays were programmed in series using ExtendSim® 8 [23] as an entire simulation segment, as shown in figure 2.

The initial probability block setting for each category was determined by dividing the number of programs that experienced the particular delay by the total number of

Overall Delay Category Statistics							
	SV-Early	SV-Late	LV-Long	LV-Short	Re-queue	Priority	Wx/Misc
Sample Size	1.36	3.24	2.21	1.70	1.67	0.79	0.82
Probability of Delay Within Category	11.6%	27.5%	18.8%	14.4%	14.1%	6.7%	6.9%
Mean Delay	4.05	1.16	1.57	0.56	1.99	2.07	0.18
Median	35.0%	10.0%	13.6%	4.9%	17.2%	17.9%	1.5%
Std Dev	5.52	3.77	3.48	0.95	3.32	1.63	0.14
Min Delay	29.3%	20.0%	18.5%	5.1%	17.6%	8.7%	0.8%

Table 4: Overall Delay Category Statistics

Consolidated Delay Statistics							
	SV-Early	SV-Late	LV-Long	LV-Short	Re-queue	Priority	Wx/Misc

	Satellite Vehicle	Launch Vehicle or Process
% Time Delayed per Program	49.4%	50.6%

	Satellite Vehicle	Launch Vehicle	Launch Process or Range
% Time Delayed per Program	49.4%	23.5%	27.1%

	Satellite Vehicle	Launch Vehicle	Launch Process	Wx/Misc
% Time Delayed per Program	49.4%	23.5%	26.3%	0.8%

Table 5: Consolidated Delay Statistics

programs. This determined the probability a particular program would experience a delay within a particular category. This calculation was derived using table 3 data.

$$P_{initial} = \text{\# of programs delayed in category / \# of total programs} \quad (1)$$

If a program did encounter an initial delay, the second delay block determined the probability of additional delays within the same category. This probability was estimated by taking the reciprocal of the average number of additional delays. This approximation was accurate when the average number of additional delays was greater than one. In the two cases when it was not greater than one, Priority and Wx/Misc, the team used experience to estimate the probability on an additional delay:

$$P_{additional} = 1 - \{1 / [(\text{avg \# of additional delays per program per category})]\} \quad (2)$$

The actual time delays themselves were simulated in ExtendSim using activity blocks. The activity blocks simulate a time delay via a randomly-seeded sampling of a preassigned distribution. Each pass through the activity block simulates an individual delay occurrence and then flows back into the decision block to determine if another iteration of the delay will occur. If not, it will flow on to the next delay category, as depicted in figure 2.

We chose the proper distributions for each activity block after analysis of the actual program delay data. Statistical analysis was conducted on each delay category's actual data, shown in table 6.

An analytical probability density function (PDF) was chosen to best approximate the empirical histogram data in each category. In most cases, the inverse Gaussian function most closely approximated the delay data. Microsoft Excel Solver plugin [24] was used to minimize the cumulative

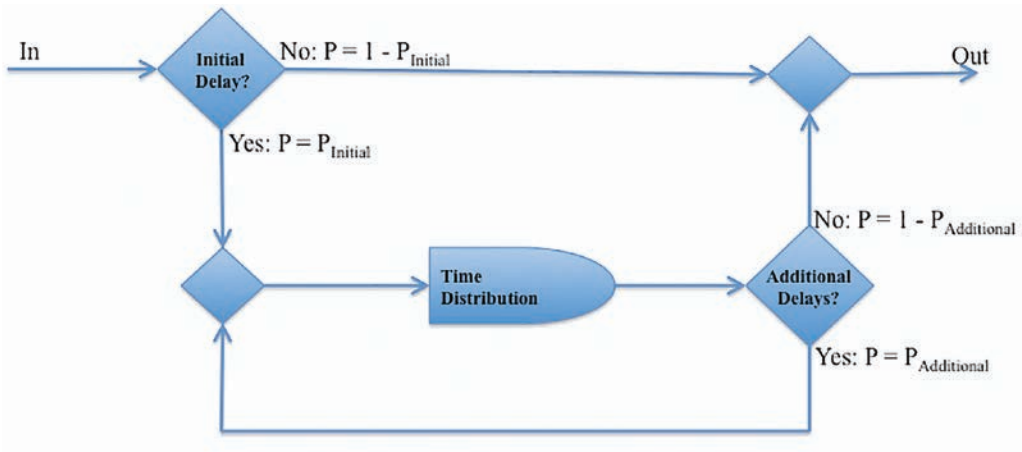

Figure 1: Example of Individual Delay Category Loop

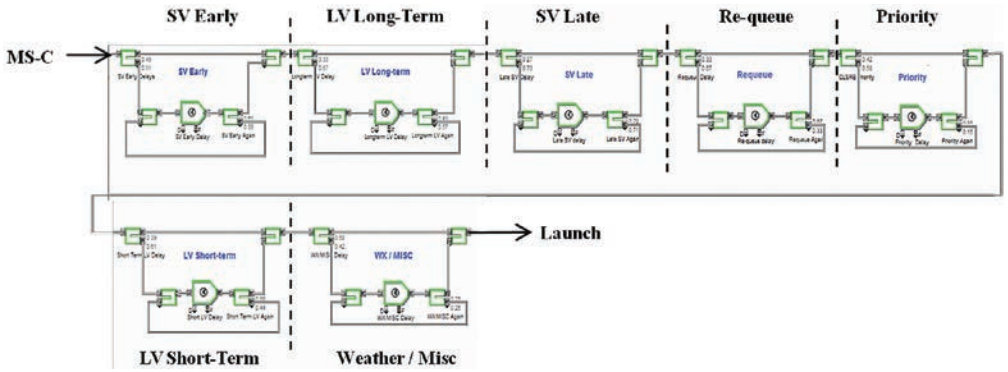

Figure 2: Model as Depicted in ExtendSim

squared error between the histogram data and the cumulative distribution by optimizing the inverse Gaussian parameters, α and β. The following equation describes this technique:

$$\min_{(\alpha,\beta)} \sum_{i=1}^{N} (F_i - H_i)^2 \tag{3}$$

where:

α and β are input parameters to the inverse Gaussian function,

F_i is the Cumulative Distribution Function evaluated at histogram point *i*,

H_i is the normalized histogram value at point (bin) *i*, and

N is the total number of histogram points.

Two particular delay category histograms, SV–Early and Priority, did not closely fit an inverse Gaussian distribution or any other distribution. In these cases, simple triangular distributions were used, with minimum, maximum, and most likely values set by observation, excluding statistical outliers [16]. This use of triangular distributions was the technique predominantly used within the entire ERAM simulation [7]. The distribution parameters used in the model are shown in table 7. The histograms for each delay category along with the selected overlying distributions, *F*, are shown in figure 3.

	Inverse Gaussian		Triangular		
Delay Category	**α**	**β**	**Minimum**	**Maximum**	**Most Likely**
SV-Early			-3	12	4
SV-Late	1.2	3			
LV-Long Term	1.1	1.8			
LV-Short Term	0.01	0.1			
Re-queue	0.59	4.97			
Priority			-4	10	1.3
Wx/Misc	0.152	0.159			

Table 7: Delay Category Distribution Parameters

Running and Verifying the Simulation

Our team verified the model by comparing two criteria between actual and modeled data. The first element compared was the average number of times a program or simulation experienced the individual delay categories. This assessment was used to verify the accuracy of the probability blocks used to simulate delay occurrences. Matching the empirical standard deviation, the Student's t-distribution can be used to determine the minimum number of Monte Carlo replications to achieve a relative precision and significance level. For a 0.05 precision and significance, 473 replications were required; however, a total of 1000 replications were used.

In each delay category, the model simulations experienced fewer occurrences on average than the actual launch programs. This difference ranged from 16–41% among

	SV-Early	SV-Late	LV-Long	LV-Short	Re-queue	Priority	Wx/Misc
# of "No Delay"	16	9	11	13	11	14	19
Total Programs	33	33	33	33	33	33	33
Probability of First Delay ($P_{initial}$)	0.51	0.73	0.67	0.61	0.67	0.58	0.42
1 - $P_{initial}$	0.49	0.27	0.33	0.39	0.33	0.42	0.58
(Average of "Non-0" Delays) - 1	1.64	3.45	2.31	1.80	1.50	0.36	0.92
Probability of Additional Delays ($P_{additional}$)	0.61	0.29	0.43	0.56	0.67	0.85	0.75

Table 6: Overall Delay Occurrence Statistics

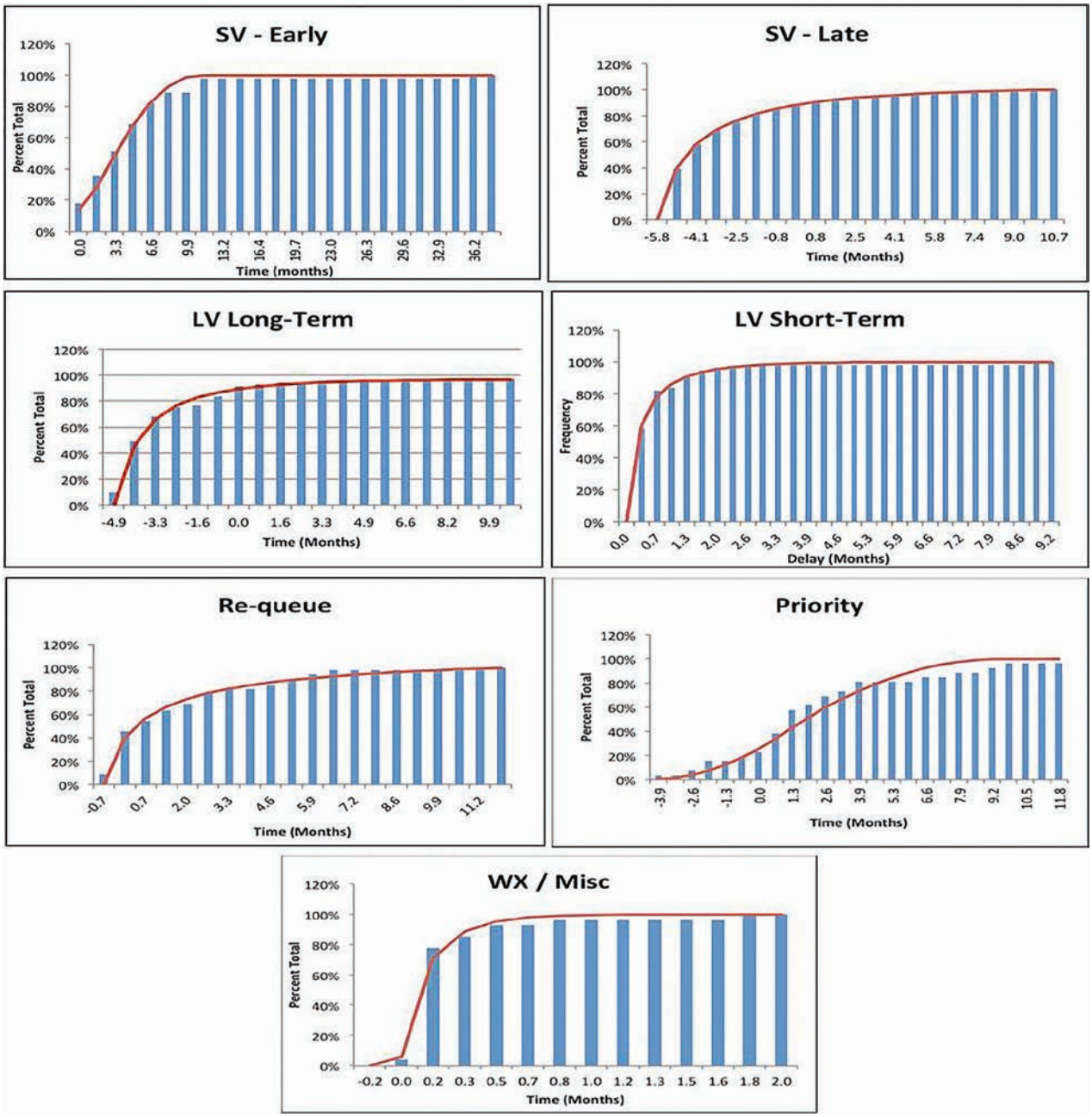

Figure 3: Delay Category Modeled Distributions (line) and Empirical (bar)

the delay categories. The team considered this difference substantial, but accepted it as within reasonable error bounds given the variance of the sample data and relative accuracy of the overall simulation results.

The chosen model most likely underestimated the number of delay occurrences because multiple delays were simulated using only two probabilities, $P_{initial}$ and $P_{additional}$. This technique was used to simulate the potential for three or more delays of each type, while minimizing overall complexity and maximizing flexibility within the model. The error had a "delay shortening" affect on the overall model results. Additionally, inverse Gaussian distributions used to simulate most of the delay categories have an infinitely long "tail". The team assessed the combination of the above discussed "delay shortening" occurrence estimation error and the "delay lengthening" distribution

error actually combined to form an accurate end result. Results of the basic statistics are shown in table 8. The difference in mean program delay between actual and modeled data is within 1%, with a difference in standard deviation of 4%.

	Mean	Std Dev
Model Results	18.62	11.58
Actual Results	18.82	12.08
Difference	1%	4%

Table 8: Model (1000 Replications) vs. Actual (33 Program) Delay Statistics

The histograms of the model and actual data, shown in figure 4, provide a comparison of the respective distributions. Both distributions appear to display a bi-modal nature. Actual data appears to have modes at approximately 2 and 20−30 months, while the model outputs modes at 2 and 10−20 months, albeit with a larger tail. Possible reasons for this bi-modal nature are discussed in the Summary and Recommendations section.

Finally, a two-sample Kolmogorov-Smirnov (K-S) test was performed to test for like distributions between the model and actual data. The K-S test is a nonparametric test used to compare a sample's empirical distribution function (EDF) to a reference cumulative distribution function (CDF) [17]. In this case, the simulated data was treated as the reference CDF; the actual overall program delay data was the sample EDF. The test statistic is calculated under the null hypothesis that both samples are drawn from the same distribution. At a significance level of 0.05, the test statistic was 0.1677, with a p-value of 0.3019. The result failed to reject the null hypothesis that both samples are from the same distribution.

Summary and Recommendations

Using SMEs, together with LISN launch change request data, we were able to create a serial and iterative model of EELV space launch delays. The average program experienced a delay of 18.82 months, but appears to experience variation on the characteristics of the satellite program. Technologically-mature programs face fewer threats to a schedule and therefore tend to have fewer slips in the integration, testing, and launch phases. In comparison, those space systems with significant complexity, either technological or integrative in nature, tend to experience significantly greater delays.

First, our team identified seven delay categories for use in describing space acquisition schedule delays. These categories were classified as: Space Vehicle-Early (>18 months from launch), Space Vehicle-Late (<18 months), Launch Vehicle-Long Term (>18 months from launch), Launch Vehicle-Short Term (<18 months), Re-queue, Priority, and

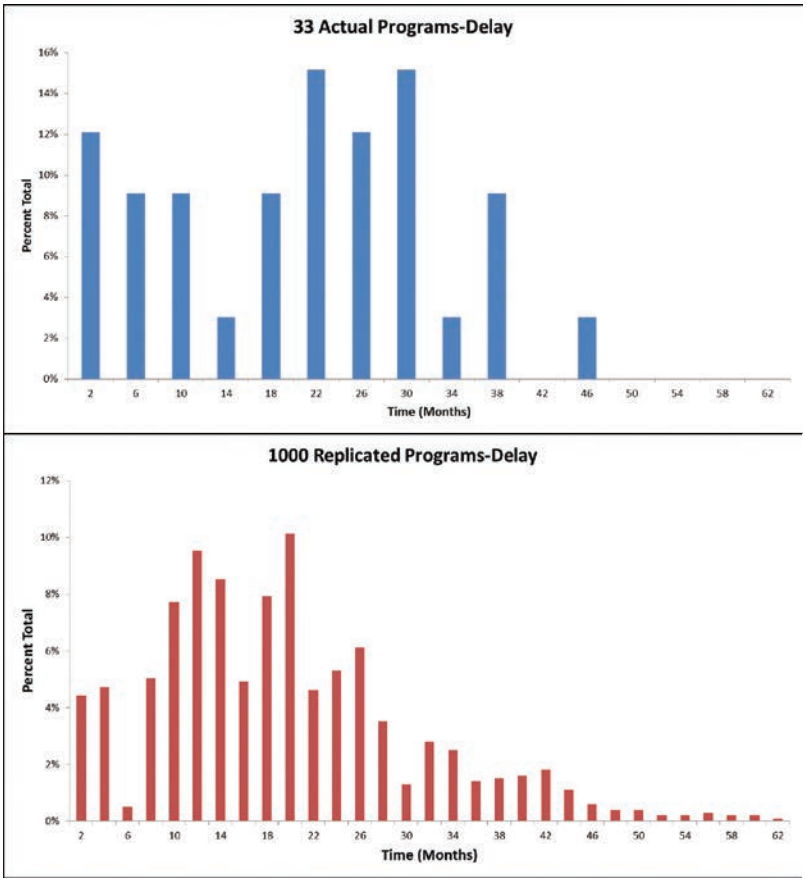

Figure 4: Model and Actual Histograms of Total Program Delay

Weather/Miscellaneous. The statistics on the frequency and length of each category delay was documented.

The second finding was that no statistical difference exists between the Atlas V and Delta IV launch vehicles with respect to schedule delays. This conclusion was based on data collected from 33 historic launch schedules with almost 400 launch change requests. The data showed that delays within each of the seven delay categories can vary significantly for both launch vehicles, but an average delay in each group cannot be statistically separated.

Third, historical delay data exhibited some bimodality, with a mode at a few months and a secound mode approximately at 20 months. The team hypothesizes that this bimodality may be associated with specific aspects of the space vehicle program. The characteristics most noted were: multi-satellite procurements, varying technology risks, varying satellite complexity, contractor risk, and the confidence associated with original programmatic schedule estimates. Often, individual delays are unforeseeable and are caused by manufacturing issues or issues associated with another mission [18]. A relatively small number of programs caused the short-delay mode at approximately two months; the SMEs reported that programs have the ability to accelerate if there is significant impetus and close coordination between all components of the acquisition process. Lastly, the team found that an urgency of need has shown the ability to drive a program closer to an estimated schedule.

Recommendations and Future Work

Based on SME discussions, current scheduling tools are fairly accurate; however, the perception is that a realistic program schedule often doom the program in terms of support. This leads to creation of "green-light" program schedules in an effort to compete with other programs for scarce funding. These "green-light" optimistic schedules will only be achieved if every aspect of a long complex space vehicle development goes flawlessly. Based on historical data, the probability of meeting a "green-light" schedule is very low. The acquisition community must overcome this cultural artifact. Some recent efforts have looked at macro-stochastic estimating taking into account empirical changes to baselines [23].

In concert with increasing schedule margins to account for expected schedule delays, space programs should continue to assess a "green-light" schedule. However, similar to the "Will cost" and "Should cost" estimation management implemented across DoD acquisition [19], satellite acquisition offices should consider implementing two schedules, a "green-light" and "most-likely" schedule. Acquirers should vigorously pursue the "green-light" schedule with satellite contractors; however, leadership at all levels should be aware that these schedules are often unobtainable and that the "most-likely" schedule will best suit planning purposes for budgetary and requirements discussions.

Lastly, the space community should implement better practices for tracking historical program timelines and associated causes of delay. This data should be used to ensure lessons learned are properly vetted and passed between programs to alleviate schedule growth issues. Furthermore, future analysis similar to that conducted in this study can target specific areas for schedule improvement.

Research is continuing to analyze the acquisition process using a discrete event simulation, such as ERAM. Such extensions are adding fidelity to the Test and Evaluation subprocesses, and revalidation of the full end-to-end model with more empirical data. Proposals include an Agent-Based Modeling extension to capture complex inter-organizational behaviors, incentives and rules. ERAM could be extended to encompass other launch vehicles such as the Delta II Medium Launch Vehicle, future launch capability estimates for SpaceX, Orbital Sciences, and other potential commercial launch vehicles. There exists an opportunity for significant sensitivity analysis of the Space Launch model and its interaction across the DoD acquisition process captured in ERAM.

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Standards Profiles – A Blueprint for Decision Makers to Effectively and Efficiently Apply Modeling and Simulation (M&S)

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Abstract

BUILDING BLOCKS FOR MODELING AND SIMULATION (M&S) INTEROPERABILITY, REUSABILITY AND INCREASED CAPABILITY INCLUDE GOVERNMENT, INDUSTRY, AND INTERNATIONAL STANDARDS DEVELOPED BY COMMUNITIES OF PRACTICE. HOWEVER, STANDARDS ARE ONLY VALUABLE WHEN DISCOVERED, DEEMED APPLICABLE AND USED. UNDERSTANDING ALL THE KEY AREAS WHERE STANDARDS APPLY IS OFTEN DIFFICULT. NUMEROUS CHALLENGES TO IDENTIFYING AND APPLYING M&S STANDARDS ACROSS THE DoD ENTERPRISE REMAIN. WITHOUT DIRECT KNOWLEDGE OF THE EXISTENCE, PURPOSE AND APPLICATION OF STANDARDS, THE ABILITY TO SELECT AND APPLY SPECIFIC STANDARDS TO CERTAIN AREAS OF M&S IS LIMITED AND POSSIBLY INEFFECTIVE. INCREASED KNOWLEDGE, SHARING AND UNDERSTANDING OF STANDARDS CAN FILL THAT VOID WITH THE DEVELOPMENT OF STANDARDS PROFILES. STANDARDS PROFILES INCLUDE A COMPILATION OF RECOMMENDED STANDARDS METADATA CITATIONS AND RECOMMENDED PRACTICES FOR STANDARDS THAT SUPPORT SYSTEM ENGINEERING ACTIVITIES THAT BENEFIT FROM M&S. EXAMPLES INCLUDE THE TECHNICAL COOPERATION PROGRAM (TTCP) SIMULATION INTEROPERABILITY STANDARDS GUIDELINE AND THE NATO M&S STANDARDS PROFILE, THIS ARTICLE DISCUSSES THE VALUE AND POTENTIAL OF STANDARDS PROFILES AND EXAMINES HOW THE DEVELOPMENT AND ADOPTION OF TAILORED STANDARDS PROFILES MAY BE APPLIED BY ORGANIZATIONS, PROGRAMS OR PROJECTS TO PROMOTE EFFECTIVE M&S. BENEFITS DERIVED INCLUDE CONSISTENCY, REUSE, COHERENCY, AND EFFICIENCY WITHIN DOD COMMUNITIES OF PRACTICE; E.G., ACQUISITION, ANALYSIS, EXPERIMENTATION, INTELLIGENCE, PLANNING, TESTING / EVALUATION, AND TRAINING.

Introduction

Mr. Stephen Welby, Deputy Assistant Secretary of Defense (Systems Engineering), recently stated, "For our modeling and simulation efforts to be affordable, efficient, and effective, we need to facilitate data exchange and reuse between models and simulation systems, across applications and databases, and across disciplines. Common and shared technical standards provide the foundation and basis that allow modeling and simulation (M&S) tools to be efficiently and effectively deployed and scaled to address enterprise challenges [1]."

Standards applied in the development and application of models and simulations increase effectiveness and efficiency while reducing risk, removing ambiguity and lowering costs. However, common, accepted and experience-based guidance is needed to support the needs of M&S development and application efforts to identify, select and apply the most appropriate M&S standards and recommended best practices. Standards Profiles provide a method to more readily discover, identify and document standards and recommended practices. The resulting use of these standards can better enable decision making activities across respective Department of Defense (DoD) communities of practice and across complex application domains.

A Standards Profile is needed for the Acquisition Community to address challenges faced in the acquisition of complex systems to apply M&S in consistently meaningful ways [2].

This article discusses the value and potential of Standards Profiles and examines how the development and adoption of tailored Standards Profiles may be applied by organizations, programs or projects to address multiple challenges facing the Acquisition Community and other functional application communities.

The analogy of architecture blueprints (or architecture drawings) is applied in this article to introduce and illustrate the role, importance, value and potential of Standards Profiles in development of many types of models and the application of simulations. Blueprints are intended to communicate design intentions in a clear manner just as Standards Profiles can assist programs and projects by identifying the most appropriate set of standards to apply at key points in the respective M&S development and service activities [3].

A Blueprint for Decision Makers

Blueprints are developed through the use of common rules and standards and serve as key tools to ensure that architecture designers and decision makers are able to understand and communicate effectively with each other. These blueprints make clear what is required by the design. Builders are able to conform to the blueprints and build effective structures compliant with current rules and regulations.

Standards Profiles serve as these blueprints and are key tools to provide communities and their respective decision makers the information they need about the existence, availability and capability of relevant standards and best practices that can be used in the development and application of M&S.

Benefits and Value

In addition to providing communities with tailored collections of relevant standards and best practices, the consensus-based process employed for development of Standards Profiles also encourages professional dialogue among community leaders. Discussion reflects community challenges faced in implementing standards and provides opportunities to establish ways forward to overcome numerous impediments. Standards serve a critical function, much like building codes in construction.

Standards are very important tools for achieving goals in terms of M&S effectiveness, efficiency and usability. Standards are increasingly being seen as a means of achieving other M&S goals such as better return on investment, interoperability, reusability and increased capacity [4].

Challenges to Overcome

Over the course of the past two decades, in areas of rapid technical and programmatic innovation, M&S standards have too often been less than welcome because of perceptions that such standards would impede program flexibility and/or increase program costs. Standards Profiles, as recommended collections of standards, may also be met with hesitation and concern. The listing below provides some specific historical impediments to standards usage [5].

- Concern Over the Unknown
- Support for Legacy Systems
- Program vs. Enterprise Goals and Requirements
- Budgets and Schedules
- 'Not Invented Here' Syndrome
- Perception of Loss of Control Over Project
- Rapid Technological Change
- Immediate vs. Future Needs
- Local vs. Global Needs

These concerns remain as challenges to overcome despite the fact that the value of standards has been understood and demonstrated repeatedly.

Similarly, a multi-year study conducted by the Virginia Modeling Analysis and Simulation Center (VMASC) included a summary of findings from the third year of the study, which focused on the financial benefit of standards. Those findings, addressed in a Simulation Interoperability Standards Organization (SISO) Simulation Interoperability Workshop (SIW) paper, [4] included identification of several organizational misbehavior areas, which included persistent obstructionism, malicious compliance and sloppy implementation as misbehavior within the development of M&S standards. Various causes for these behaviors are discussed in the paper.

However, the professional dialogue, research, education and awareness included in the approach for developing and executing a Standards Profile can assist to overcome many of these challenges. Ways to mitigate these and other challenges are noted below [5].

- A focus on Community User Requirements
- Broad Based Community Participation
- Wide Community Review and Comment
- Technical Usage and Community Buy-In
- Successful Testing in Realistic Situations

Perhaps the effort to develop a Standards Profile is not just the development of a product but in addition serves as the foundation and stimulus for change in the culture of M&S standards application. It may also foster improved proactive understanding of the value in standards.

The Potential For A Standards Profile – One Community's Story

DoD has developed and follows a structured systems acquisition process, as illustrated in figure 1. As shown, live-virtual-constructive (LVC) M&S is applied across a system's life cycle, supporting the three major phases of pre-systems acquisition analysis, systems acquisition and sustainment. M&S supports a broad community of practice, spanning Acquisition, Analysis, Experimentation, Intelligence, Planning, Test and Evaluation and Training.

Figure 1, clearly illustrates the fact that M&S standards can play a key role in achieving the Department's acquisition goals. In fact, the use of open, collaboratively developed standards is encouraged by the Office of Management and Budget (OMB) Circular A-119 across the entire Federal government. That circular, originally published in 1998, establishes policies on Federal use and development of voluntary consensus standards and on conformity assessment activities [6]. Public Law 104-113, the National Technology Transfer and Advancement Act of 1995, codified existing policies in A-119, established reporting requirements and authorized the National Institute of Standards and Technology to coordinate conformity assessment activities of the agencies. It is important to recognize that standards (just like building codes) are an important part of the process of inter-discipline communication and construction. Although standards support and encourage user compliance, the enforcement of standards alone is insufficient to construct a new model, build a new simulation, or modify an old one to meet emerging needs. The participants in the process, including the M&S sponsors, developers and users (among others) all have an important bearing on what gets built, how it is built and how it performs.

Models and simulations are used in support of many of the tasks and activities required to execute the acquisition of a system. Typically, these efforts are pursued as individual activities, each supporting a specific task (e.g., a functional model may be developed to support reliability analysis). Independently, a second model, including an independently developed functional architecture, will be developed to produce subsystem specifications. Meanwhile, a third model that supports analysis of operator work load that also includes a model of system functions will be developed in its own *silo*.

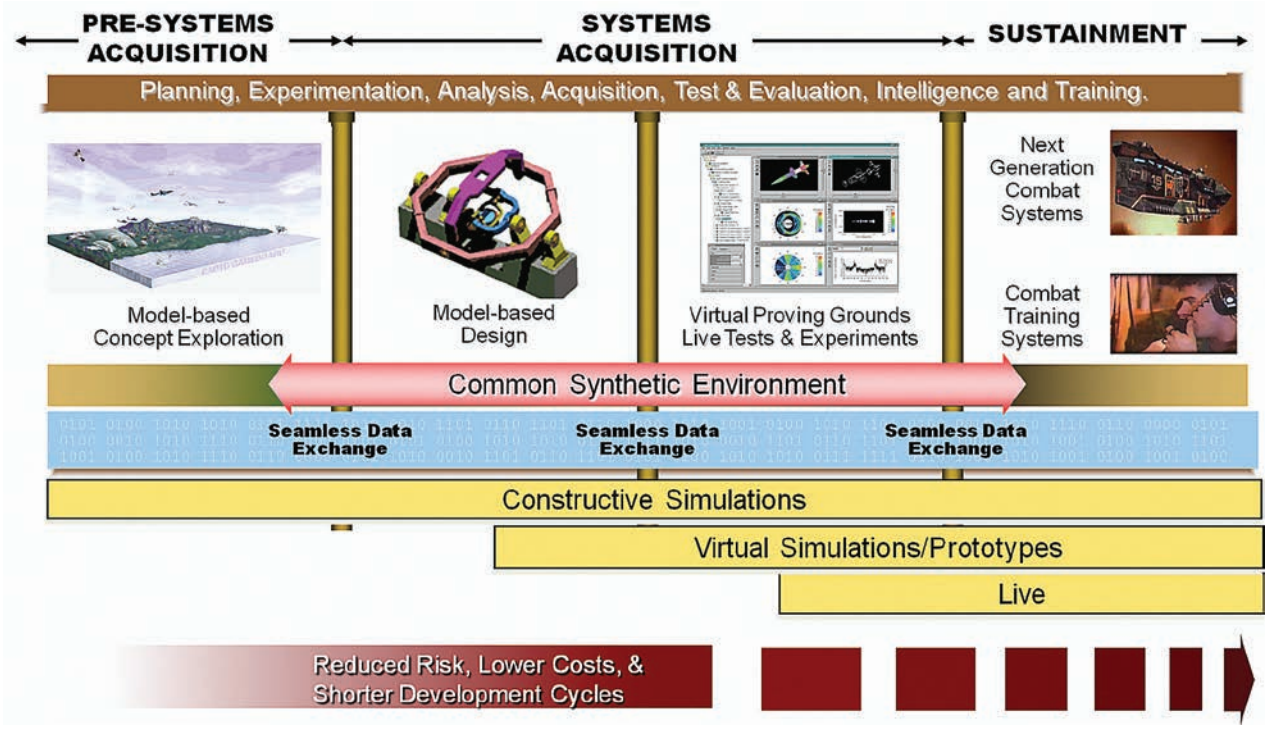

Figure 1: M&S is a Cross-Cutting Technology Supporting Programs Across the Acquisition Life Cycle

Each of these models portrays system functionality in some way. Unfortunately, a potential Tower of Babel may result with unintended duplication of effort and the likelihood of analysis being performed with an inconsistent understanding of "ground truth" as unfortunate consequences.

Furthermore, due to increasing complexity of systems (and assessment of their operational value within a designated System of Systems), it is becoming ever more apparent that there is a real need to provide access to, or transfer of, models and simulations between government and industry as a means to establish consistency and coherency. While use of data standards supporting the exchange of physical model data (e.g., 3D geometry) is coming into common use, the exchange of models representing earlier design abstractions–those used in support of analysis and specification development–typically does not occur, and is inconsistent when implemented. This status quo reflects both technical and cultural dimensions.

Numerous acquisition activities may be supported by M&S across an acquisition lifecycle and can potentially benefit from a Standards Profile that addresses recommended standards and recommended practices across the breadth and depth of today's complex acquisition programs.

As illustrated in figure 2, the potential gains to be achieved through Model-Based System Acquisition can be enabled by a Standards Profile supporting the use of modeling and simulation in support of the acquisition life cycle [2].

Context and Organization to Build the Standards Profile

"In support of our mission, it is vitally important that we provide our program managers and systems engineers with effective tools that support the design, development and deployment of the increasingly complex weapons systems and capabilities critical to our Soldiers, Sailors, Airmen, and Marines. As the complexity of our systems has increased, so has the need for effective engineering insight across the product life cycle [1]." A Standards Profile built to support the use of M&S in support of acquisition activities will enable government and industry engineers, analysts and managers engaged in acquisition, to consider the application of M&S across the typical acquisition lifecycle to address multiple issues during each program phase.

SISO has seized the initiative and is supporting development of a Standards Profile to be published as a SISO Product. The need for a Standards Profile for the use of M&S in support of acquisition community activities was communicated at the 2012 Fall SIW during a special session of the System Life Cycle (SLC) Forum [2].

To support this need, a SISO Product Nomination was approved and the new SISO Acquisition M&S Product Development Group (PDG) was stood up. The PDG is developing a SISO Guidance Product and a SISO Reference Product.

- The Guidance Product will identify a set of modeling and simulation standards and recommended practices as key tools for guiding the international acquisition community in the use of modeling and simulation in activities that take place across the typical acquisition lifecycle.
- The Reference Product will provide the descriptions and metadata for each modeling and simulation standard and recommended practice identified in the SISO Guidance Product.

Table 1 identifies the PDG Officers and Drafting Groups' Leads.

PDG Officers:	Drafting Groups / Product		
Tim Tritsch, PDG Chair	**1. Guidance Product**	**2. Reference Product**	**3. Quality Assurance**
Paul Gustavson, Vice-Chair	Paul Lowe, Lead Editor	Hart Rutherford, Lead Editor	Ralph Gibson, Lead Editor
Peggy Gravitz, Secretary	Peggy Gravitz, Co-Editor	Crash Konwin, Co-Editor	Jim Coolahan, Co-Editor

Table 1: PDG Officers and Drafting Group Leads

This product supports SISO's mission "to develop, manage, maintain, and promulgate user-driven M&S standards that improve the technical quality and cost efficiency of M&S implementations across the world-wide M&S community." Additionally, this Standards Profile effort strengthens and

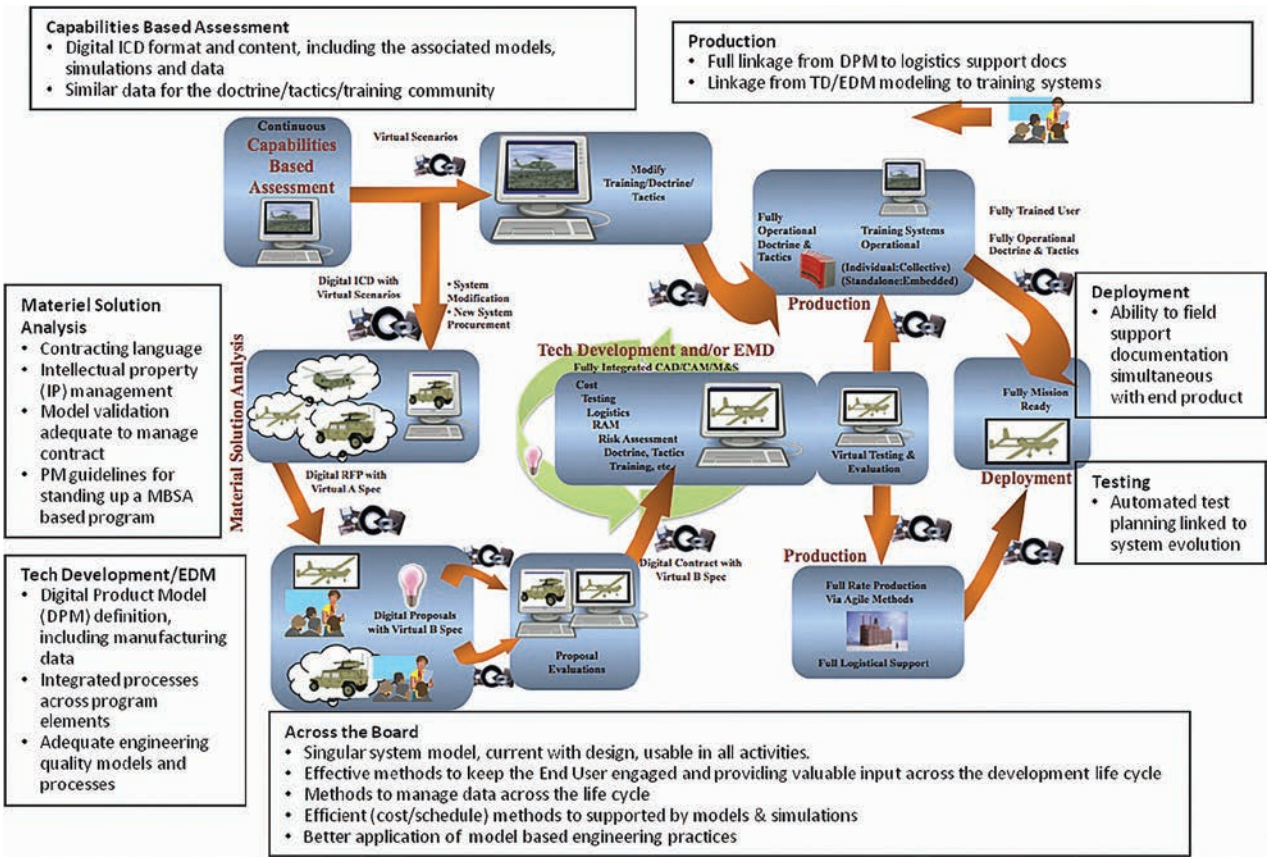

Figure 2: Model-Based System Acquisition Possibilities Are Enabled with a Standards Profile Supporting the Use of Modeling and Simulation in Support of the Acquisition Life Cycle

embraces SISO's stated vision, "SISO is the organization dedicated to the promotion of modeling and simulation interoperability and reuse for the benefit of diverse M&S communities, including developers, procurers, and users world-wide [7]."

The current product development effort also addresses the international community's desire to develop a Standards Profile to move from the present state to an agile acquisition engineering environment.

Support to Other Community Standards Needs

In the future, similar initiatives could also be championed by SISO for each community of practice represented by its membership: Analysis, Experimentation, Intelligence, Planning, Test & Evaluation, and Training. Standards Profiles for these communities of practice would address shortfalls in guidance by addressing the selection and use of standards across their spectrum of M&S use.

How You Can Participate

Individuals can participate by joining SISO and volunteering as a PDG member. Interested individuals who cannot become SISO members are welcome to contribute to the discussions and some development activities. For more information visit www.sisostds.org and select Development Groups under Standards Activities to locate the Acquisition M&S PDG [7].

Related Standards Profile Efforts

Other related Standards Profile efforts include the *NATO Modelling and Simulation Standards Profile* published and maintained by the NATO Modelling and Simulation Group (NMSG) under the title "AMSP-01 (Allied M&S Publication-01)" [8] and *The Technical Cooperation Program (TTCP) Simulation Interoperability Standards Guideline,* supported and maintained by the TTCP [9].

Determining how these profiles relate to the Acquisition Community Standards Profile will be an early technical objective of the SISO PDG. In addition to the Acquisition Community Standards Profile and other community-specific published standards, future efforts may generate profiles that can support standards needs for other communities of practice.

The Way Forward - A Living Guide

Once the final Standards Profile for the use of M&S in support of the acquisition community has been developed, vetted and approved, existing SISO processes will be applied to maintain the guidance product and the reference information on each standard included. Timelines for periodic review and update of guidance and reference products will be established so the document is periodically reviewed and revised to reflect changes in standards and practices.

Summary

In conclusion, the Acquisition Standards Profile will serve all communities that manage, develop, and/or use models and simulations in support of the acquisition, use, and retirement of systems, and system of systems. It will establish a compilation of standards and recommended practices that are used to manage, coordinate, align, and integrate the development and use of model and simulation artifacts through a systems acquisition lifecycle across both time (e.g., acquisition phases) and organizational and activity boundaries. Without a Standards Profile, product models that support simulation and analysis will continue to be built in a stove-pipe fashion. The goal of consistent and reusable models will also continue to be elusive. The current challenges faced in the acquisition of complex systems to apply M&S in consistently meaningful ways will continue to exist without the solutions this guidance product will enable. Also, the concerns of government acquisition leadership will not have been addressed.

The expected benefit to DoD in utilization of this Standards Profile includes increased efficiency and effectiveness and potentially lower cost and risk, in Model-Based Systems Acquisition [2].

In addition, the products are not limited to DoD, as they will be organizationally agnostic to the greatest degree possible and are expected to benefit all activities involved in the design, development, delivery and deployment of complex systems to accomplish organizational missions. These benefits will accrue for industry, government, and academia within the United States, as well as, across the international community.

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Authors' Biographies

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Mr. Tim Tritsch is a senior staff systems engineer with the Dynamics Research Corporation (DRC), a management consulting and information technology company. He has 25 years of experience as a systems engineer and has spent most of the last 15 focused on the application of models to support the Systems Engineering discipline. Mr. Tritsch has worked for the Naval Air Systems Command as a Logistician and Systems Engineer for U.S. Navy Aircraft and Aircraft Carrier equipment, as a consultant and trainer for the application of systems modeling at the Vitech Corporation, and though his work at DRC is currently providing support to the Deputy Director for Modeling, Simulation and Analysis within the Office of the Deputy Assistant Secretary of Defense for Systems Engineering. He is also serving as the chair of the SISO Product Development Group developing the Standards Profile described in this article. Mr. Tritsch has provided dozens of public presentations and tutorials on the subject of systems modeling and architecting and holds an Object Management Group Certification for Systems Modeling Professionals. He has a B.S. in Industrial Engineering from Lehigh University and an M.S. in Systems Management from Capitol College.

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Mr. Paul Gustavson is co-founder and Chief Technology Officer at SimVentions, Inc., has over 23 years of experience including the design and development of DoD standards, simulation systems, software applications, numerous technical publications and tutorials on simulations and software development. He is an active leader within the Simulation Interoperability Standards Organization (SISO), serving as product lead and architect of the Base Object Model (BOM) concept, is involved in other standards efforts, including the Distributed Simulation Engineering and Execution Process (DSEEP). He is also co-author of several books including *C++Builder 6 Developer's Guide*.

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Mr. Paul Lowe is a senior software/simulation engineer for The Boeing Company. He received his B.S. in mathematics (1979) and his M.S. in geography (1984) from the University of California, Riverside. Mr. Lowe has worked in the computer industry for over 34 years, specializing in the areas of high performance computing, geographic information systems, modeling-simulation-analysis, image processing, database management and knowledge management.

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Mr. Hart Rutherford is the manager of the M&S portfolio of products and services at SimVentions, Inc. Mr. Rutherford has over 20 years of professional experience as a combat systems engineer and program manager including technical leadership of M&S VV&A for the Navy's DD(X) program as well as a contributor to the development and maintenance of DoD M&S standards. Mr. Rutherford's military background includes 8 years active and reserve service in the U.S. Navy as an AEGIS Operations Specialist. He holds a Master's degree in Systems Engineering from Old Dominion University and B.S. in Computer Information Systems from Chapman University.

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Mr. Ralph Gibson is a SETA support contractor for the Modeling and Simulation Coordination Office (M&SCO), supporting the Associate Director for Services working in the areas of standards and VV&A. Previously, he was a Senior Software Engineer supporting the Joint Integrated Mission Model (JIMM) Model Management Office at the Air Combat Environment Test and Evaluation Facility, Patuxent River Naval Air Station. Mr. Gibson holds a B.S. degree in Astronautical Engineering from the USAF Academy and a Master of Software Engineering degree from the University of Maryland. He has written papers covering use of M&S in acquisition, software development, automated software testing and test development, and process improvement.

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Mr. William Oates is the Chief, Live-Virtual-Constructive Operational Training (LVC-OT) Agile Combat Support for the Air Force Agency for Modeling and Simulation (AFAMS). He is the Air Force representative on the M&S Technical Standards Working Group. He is a member of the Simulation Interoperability Standards Organization (SISO) Standards Activity Committee (SAC) which is responsible for the development of national and international M&S standards. He has a B.S. degree in Computer Information Systems Management from the University of Colorado Christian and an M.A. in Computer Resources and Information Management from Webster University. He has an extensive background in Command & Control, Computers, Communications, Intelligence (C4I) Systems and architectures.

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Mr. Kenneth Konwin has been a Booz Allen Hamilton professional for over 11 years after a 27 year Air Force career. His current assignment is providing mission support as a Senior Weapons System Analyst within the Department of Defense AT&L/ASD(R&E)/SE/Systems Analysis directorate in Washington, DC. Mr. Konwin is a past Director of the Defense Modeling and Simulation Office (DMSO), former Chairman of the NATO Modeling & Simulation Group (NMSG) within the Research and Technology Organization, and original Deputy Director of Requirements and Chief of MS&A for the Joint Strike Fighter program office. He was a distinguished graduate earning a Master's Degree in Operations Research from the Air Force Institute of Technology, and a Bachelor's Degree in Civil Engineering from the U.S. Air Force Academy. Mr. Konwin is a DAWIA trained SPRDE and PM.

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Mr. Severinghaus is currently conducting research focused on interoperability solutions to improve the technology available in the healthcare and disaster response domains, and research on team performance in high stress environments. He holds a Master's in Systems Management from the University of Southern California, Marshall School of Business.

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Modeling the Movement of Chemicals in the Environment

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Abstract

ACTIVE MILITARY RANGES CONTAIN MUNITIONS CONSTITUENTS (MC) AND METAL CONTAMINATION THAT AFFECT THE USABILITY AND FUNCTIONALITY OF TRAINING FACILITIES. RANGE OPERATIONS CAN ADVERSELY IMPACT THE ENVIRONMENT, INCLUDING HUMAN AND ECOLOGICAL HEALTH. ADDITIONALLY, ACTIVE RANGES IMPACT ENVIRONMENTAL COMPLIANCE AND RANGE SUSTAINMENT. U.S. ARMY LIVE-FIRE TRAINING AND TESTING RANGE ENVIRONMENTS MAY CONTAIN LOW-ORDER AND DUD MUNITIONS THAT MAY CAUSE RANDOM AND HIGHLY UNCERTAIN SOURCES OF MC CONTAMINATION. THESE RANGES ARE UNDER INCREASED REGULATORY SCRUTINY, WHICH IN EXTREME CASES CAN LIMIT TRAINING. THE U.S. ARMY ENGINEER RESEARCH AND DEVELOPMENT CENTER (ERDC) DEVELOPED TRAINING RANGE ENVIRONMENTAL EVALUATION AND CHARACTERIZATION SYSTEM (TREECS™) PROVIDES A SINGLE TOOL THAT BRIDGES THE GAP BETWEEN MIGRATION ASSESSMENT AND RISK MANAGEMENT AND RANGE SUSTAINMENT. IT ASSISTS ARMY ANALYSTS IN MANAGING RANGES THAT COMPLY WITH ENVIRONMENTAL QUALITY (EQ) OBJECTIVES FOR TOXIC CONSTITUENT STRESSORS. THIS SYSTEM CONTAINS ENVIRONMENTAL CHARACTERIZATION, RISK MANAGEMENT, AND EVALUATION TOOLS AND INTEGRATES THE RESULTS FOR EASE-OF-USE AND MANAGEMENT OF MC. THE TREECS AUTOMATES SCALABLE CONCEPTUAL MODEL FORMULATION AND PARAMETER POPULATION AND PATHWAYS AND FORMULATES AND COUPLES FIRST PRINCIPLE MC FATE/TRANSPORT-TRANSFORMATION-SEQUESTRATION MODELS WITH HYDRAULIC MODELS. MODEL OUTPUT ALLOWS ANALYSTS TO ADDRESS POTENTIAL MOVEMENT OF CHEMICALS ACROSS THE LANDSCAPE AND IDENTIFY BEST SAMPLING LOCATIONS FOR HISTORICAL CONTAMINATION, PERSISTENCE IN A SPECIFIED LOCATION, AND POTENTIAL CHEMICAL LOADING. THE ARMY CAN USE THE MODELING RESULTS TO OPERATE ON THEIR LANDS IN A SUSTAINABLE MANNER TO AVOID COSTLY REMEDIAL ACTIONS, AND AS A TOOL FOR EFFECTIVE RISK COMMUNICATION TO STAKEHOLDERS.

Introduction

The Training Range Environmental Evaluation and Characterization System (TREECS™) (http://el.erdc.usace.army.mil/TREECS) was developed for the U.S. Army to predict the fate of munitions constituents (MC), such as high explosives (HE) and metals, released

to the soil and transported from firing and training ranges to surface water and groundwater. The overall objective of TREECS™ is to provide environmental specialists with tools to assess the potential for migration of MC into surface water and groundwater systems. The results of these assessments can be used to assess range management strategies to protect human health and the environment from MC exposure in receiving waters. TREECS™ was developed with two levels of capability. Tier 1 consists of screening-level methods that assume highly conservative, steady-state MC loading and fate. Tier 1 requires minimal input data requirements and can be easily and quickly applied by environmental staff to assess the potential for migration into surface water and groundwater. If surface water and/or groundwater MC concentrations predicted with Tier 1 exceed protective health benchmarks at receptor locations, then further evaluation with Tier 2 is recommended to obtain more definitive results.

Tier 2 provides time-varying analyses and solves mass balance equations for both solid and partitioned phase, hereafter referred to as the non-solid phase, MC with dissolution into water. Additionally, MC residue loadings to the range soil can vary from year-to-year based on munitions use. Thus, media concentrations computed with Tier 2 should be closer to those expected under actual conditions and lower than those computed with Tier 1 due to attenuating effects. TREECS™ Tiers 1 and 2 development and initial evaluation are described in four Army ERDC technical reports [1]–[4].

TREECS™ Scope

Figure 1 is a schematic diagram of the conceptual model that TREECS™ Tier 2 addresses. The source zone for MC is the surface soil of the firing range and is referred to as the area of interest (AOI). The AOI could be the primary impact area of fired munitions, for example. The MC residue loading to the AOI must be estimated or specified. Initial MC soil concentrations within the AOI can also be specified if such information is available. In addition to the loading model, fate and transport models are included for the four media consisting of: AOI soil, vadose zone beneath the AOI soil layer, groundwater (aquifer), and receiving surface water including sediment. All of the MC fate models with TREECS™ are models of reduced form, meaning that simplifications are imposed (such as spatial dimensionality) to reduce model complexity and facilitate ease-of-use.

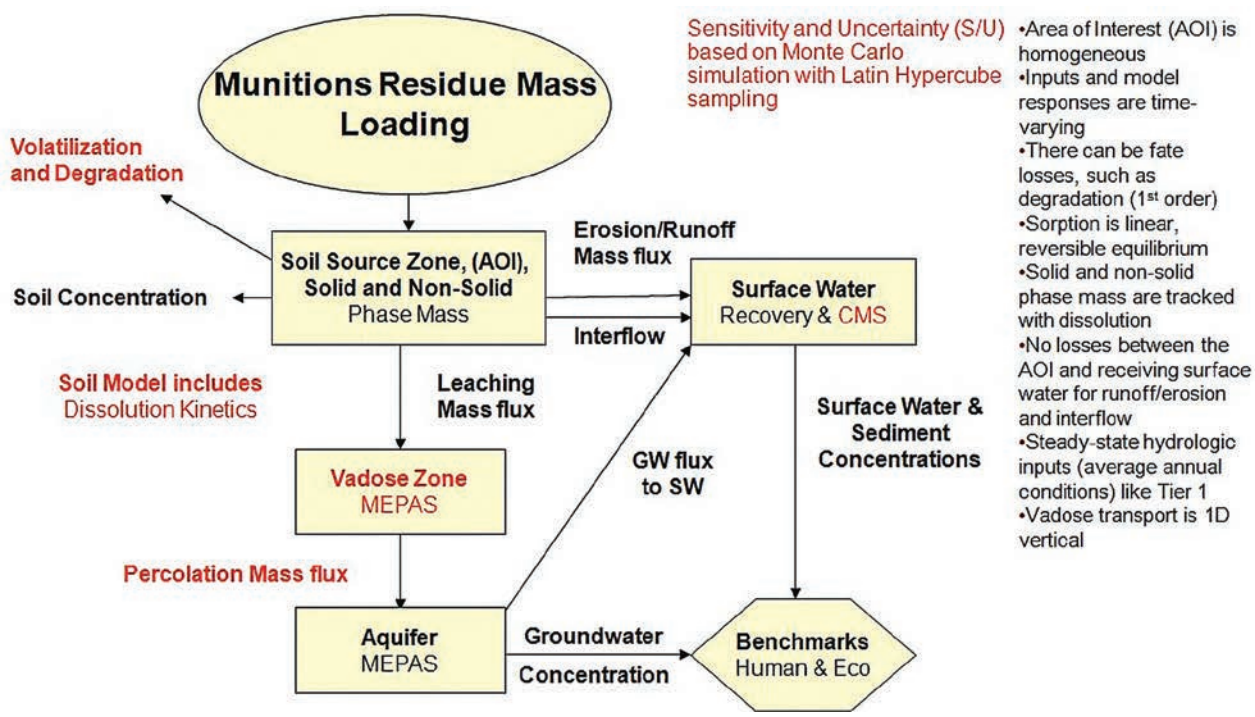

Figure 1: TREECS™ Concept

Potential environmental and human receptors could be exposed to MC if it has migrated to groundwater wells or receiving surface waters. Thus, the end point metrics are the predicted MC concentrations at target groundwater wells and the surface water body down-gradient of the AOI. These concentrations are compared to environmental and human health protective benchmarks (conservative screening values) developed by the Department of Defense (DoD) Range and Munitions Use Subcommittee to determine if more detailed site evaluations are required. Each of the models within TREECS™ Tier 2 is described in the next section.

TREECS Model Descriptions

AOI Loading Model

The two basic options within the AOI loading model are: estimate DoD range MC loadings stemming from munitions fired on range, and specify a general source loading for other scenarios. The latter option is a table of loading rates per year (g/yr) for each constituent of concern; thus, this option could be used for applications that do not pertain to firing and training ranges. The range MC loading model functions as described below.

For each munitions item used on a range, the user first selects the munitions identification using the munitions type and the Department of Defense identification code (DODIC) or national stock number (NSN). For each item, the user then provides the following for each year of input:

- The years that the item was used
- The number fired each year
- The percentage of duds for each year
- The percentage of low order detonations for each year
- The percentage yield (portion of MC used up when munitions explode) for low order detonations for each year
- The percentage of duds that are sympathetically exploded by another detonation for each year
- The percentage yield for sympathetic detonations for each year
- The percentage yield for high order detonations for each year

The percentage of high order detonations is calculated from 100 percent minus the percentages of duds and low orders. Guidance from other work is provided within the TREECS™ help files for estimating dud and low order rate and yields since these are not usually known or reported. Although sympathetic detonations can be included, inputs for these are not known and either must be assumed or set to zero. The item usage per year is stepped; i.e., the input numbers are assumed to be constant until the next update year in the input table. The amount of MC mass in each munitions item must be known to compute the MC residue loading. This information can be obtained from the Munitions Items Disposition Action System (MIDAS) (https://midas.dac.army.mil/), based on DODIC or NSN. However, extraction of information from MIDAS can be slow and tedious. A utility was developed for automatically pulling this information into the TREECS™ application using the DODIC or NSN. This utility requires a special, processed subset database of MIDAS that was developed by the Defense Ammunition Center (DAC). The MIDAS subset database includes data for 1,500 items by NSN.

Once the MC mass delivered to the impact area is known for each munitions item used and the other input parameters are entered, the calculation of residue mass loadings is a straightforward summation. The MC residue mass loading for constituent *i* for year *k*, $L_{i,k}$, (g/yr), is computed as follows,

$$L_{i,k} = \sum_{j=1}^{j=n} \left\{ N_{j,k} M_{i,j} \left[\frac{LO_{j,k}\left(100 - Y_{LOj,k}\right) + HO_{j,k}\left(100 - Y_{HOj,k}\right) + DUD_{j,k} SYM_{j,k}\left(100 - Y_{SYMj,k}\right)}{100} \right] \right\} \quad (1)$$

Where:

$DUD_{j,k}$ =	percentage of duds for munitions item j for year k
$HO_{j,k}$ =	percentage of high order detonations for munitions item j for year k
$LO_{j,k}$ =	percentage of low order detonations for munitions item j for year k
$M_{j,k}$ =	mass of constituent i in munitions item j delivered to impact area, g/item
$N_{j,k}$ =	number of munitions item j fired for year k
n =	total number of munitions items used at AOI
$SYM_{j,k}$ =	percentage of sympathetic detonation of duds for munitions item j for year k
$YHO_{j,k}$ =	percentage yield of munitions item j due to high order detonation for year k
$YLO_{j,k}$ =	percentage yield of munitions item j due to low order detonation for year k
$YSYM_{j,k}$ =	percentage yield of munitions item j due to sympathetic detonation for year k

AOI Soil Model

The soil model, figure 2, is described in more detail than the other media models since this is a new model. The AOI surface soil is treated as a homogeneous, fully mixed compartment with a thickness Z_b (m) and a surface area A (m^2), which are both constant over time. Treating a heterogeneous AOI as homogeneous is not a compromising assumption because the total MC source mass loading and/or inventory are the driving variables for AOI mass export, not MC concentration, since the model is mass balance based. Thus, the mass export from the AOI to other media does not depend on AOI surface area or volume or the AOI MC concentration [1], [3].

Each constituent can exist in solid and non-solid (water-dissolved from solid) phases. The non-solid phase mass exists in equilibrium distributed as dissolved in water within the water-filled soil pore spaces, as adsorbed from water to soil particles, and as a vapor in air within the air-filled pore spaces. A time-varying mass balance is performed for both the solid and non-solid phases.

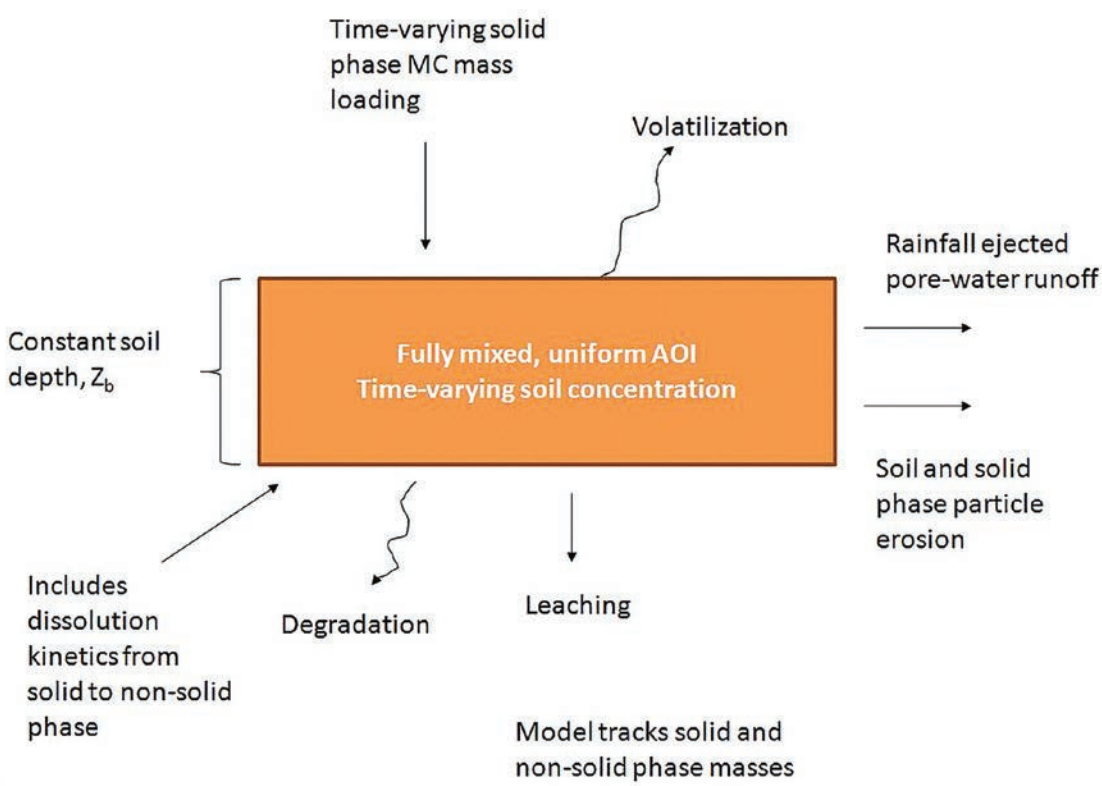

Figure 2: TREECS™ Soil Model

The solid phase mass balance is stated as:

$$\frac{dM_s}{dt} = L(t) - F_{dis} - F_{es} + F_{precip} \tag{2}$$

where M_s is the solid phase mass (g), t is time (yr), $L(t)$ is time-varying solid phase constituent mass loading (g/yr), F_{dis} is dissolution flux (g/yr), F_{es} is the erosion flux of solid phase constituent particles (g/yr), and F_{precip} is the precipitation flux (g/yr) of constituent due to dissolved pore water concentration exceeding the water solubility limit. The non-solid phase mass balance is stated as:

$$\frac{dM_{ns}}{dt} = F_{dis} - F_r - F_e - F_l - F_{decay} - F_{vol} - F_{precip} \tag{3}$$

where M_{ns} is non-solid phase constituent mass (g), F_r is the rain-induced pore water ejection and runoff flux (g/yr), F_e is constituent flux due to soil erosion (g/yr), F_l is leaching flux (g/yr), F_{decay} is degradation flux (g/yr), and F_{vol} is volatilization flux (g/yr). The total (particulate or adsorbed to soil, dissolved, and vapor) non-solid phase constituent concentration within the soil matrix on a total volume basis, C_{tt} (g/m^3) is:

$$C_{tt} = \frac{M_{ns}}{V} = \frac{M_{ns}}{AZ_b} = \frac{M_d + M_p + M_a}{AZ_b} \tag{4}$$

where V is the surface soil compartment (AOI) volume (m^3). The terms, M_d, M_p, and M_a are the constituent mass (g) dissolved, adsorbed to soil particles, and in air, respectively. The total non-solid concentration can be expressed as the sum of the three media concentrations,

$$C_{tt} = \theta_w C_l + (\phi - \theta_w) C_g + \rho_b C_a \tag{5}$$

Where:

C_l =	concentration dissolved in pore water or liquid phase, M_d/V_w, g/m^3
C_g =	vapor or gas concentration in air, M_a/V_a, g/m^3
C_a =	concentration adsorbed to soil particles, M_p/M_{soil}, mg/kg
θ_w =	soil volumetric moisture content or ratio of water volume to total volume, fraction; θ_w can't be greater than soil porosity
N =	soil porosity or ratio of void volume to total volume, fraction
ρ_b =	soil dry bulk density, g/ml or kg/L
V_w =	volume of water in the AOI soil, m^3
V_a =	volume of air in the AOI soil, m^3
M_{soil} =	mass of soil in the AOI, g

The vapor and particulate concentrations can be related to the liquid concentration through phase equilibrium partitioning, or $C_a = K_d C_l$ and $C_g = K_H C_l$, where K_d (L/kg) is the distribution coefficient for partitioning a constituent between soil particles and water, and K_H is the dimensionless Henry's constant for partitioning between air and water. Substitutions result in $C_l = \frac{C_{tt}}{\theta_w R}$ where the retardation factor R is defined as:

$$R = 1 + \frac{(\phi - \theta_w) K_H + \rho_b K_d}{\theta_w} \tag{6}$$

The leaching flux is computed from $F_l = q_w A C_l$ where q_w is the average annual Darcy water infiltration rate (m/yr). Although the soil model is time-varying, average annual values are used for the hydrologic input variables, which greatly simplified model input requirements without compromising the long-term fate calculations. The degradation flux is computed from $F_{decay} = AZ_b(\lambda_l \theta_w C_l + \lambda_a \rho_b C_a)$ where λ_l and λ_a a are the degradation rates (yr^{-1}) for the liquid (aqueous dissolved) and aqueous adsorbed concentrations, respectively. Degradation of the solid phase constituent is not presently included in the model. It is assumed that the vapor phase does not degrade, but it can volatilize or diffuse from the soil into the overlying air. The volatilization flux is computed from $F_{vol} = K_v A(\phi - \theta_w) C_g$ where K_v is the volatilization rate (m/yr), or vapor escape rate from soil to the overlying air. The erosion flux is computed from $F_e = EAC_{tt}$ where E is the average annual soil erosion rate (m/yr).

Following the work of Dortch et al. [3], [5] present the derivation of the annualized rain-induced pore water ejection and runoff flux, which is computed from:

$$F_r = Ad_e\left(1-e^{-\kappa}\right)C_{tt}N \tag{7}$$

where N is the average number of rainfall events a year, and d_e is the soil exchange layer thickness (m). The variable κ is defined as:

$$\kappa = \frac{a\phi F_{dp}P_r}{\rho_b\theta_w d_e N} \tag{8}$$

where a is the soil detachability (kg/L); N is the saturated water content, which is the soil porosity; P_r is the average annual rainfall (m/yr); and F_{dp} is defined as:

$$F_{dp} = \frac{\theta_w}{\theta_w + \left(\phi-\theta_w\right)K_H + \rho_b K_d} = \frac{1}{R} \tag{9}$$

Starting with the relationship of solid phase particle dissolution into a liquid [3], [6] derive an annualized dissolution flux,

$$F_{dis} = P_t\alpha M_s C_s \tag{10}$$

where P_t is the average annual total precipitation (m/yr), C_s is the constituent solubility in water (mg/L), and α is the average specific surface area (m^2/g) of the solid phase mass, which depends on the size and shape of the solid phase particles and the constituent solid phase density. For spherical particles, $\alpha = \frac{6}{\rho_{sm}d_i}$, where ρ_{sm} is the solid phase constituent mass density (g/m^3), and d_i is the average particle diameter (m). Dortch et al. [3] showed that the above dissolution formulation is similar to previously reported dissolution models [7]–[10]. Dortch et al. [3] also showed that dissolution rates computed with Equation 10 compare favorably with both experimental results reported by [10] and their linear model.

The average particle diameter d_i and the specific surface area α vary with time as mass is dissolved from the particles. For a constant particle density, it can be shown [11] that the average particle diameter d_i can be related to total particle mass M_s, which varies over time, with the result:

$$d_i(t) = d_i(t-\Delta t)\left\{\frac{M_s(t)}{M_s(t-\Delta t)}\right\}^{1/3} \tag{11}$$

where t is time, and Δt is the time step in the solution procedure. Since M_s is being calculated each time step, d_i and thus α can be computed for each time step. Particle size can shrink and expand, but it is not allowed to expand beyond the initial size. The exponent of Equation 11 is a result of assuming spherical particle shape.

Volatilization from soil was evaluated by Jury et al., [12] by using vertically one-dimensional (1D) soil models where contaminant concentrations vary over soil depth as a result of diffusion within the soil, volatilization across the soil-air interface, and other processes, such as leaching and degradation. A simpler approach was required in this model since the soil is treated as a single homogeneous layer, which precludes computing time-varying concentrations that vary with soil depth. The volatilization mass transfer rate K_v (m/yr) is a transport coefficient across the soil – air boundary that can be approximated as the diffusion coefficient of the vapor divided by the diffusion length or thickness for mass transfer. The effective diffusion rate coefficient for a vapor within air spaces of the soil matrix can be estimated from [13],

$$D_{G_{eff}} = D_G^{air}\frac{\left(\phi-\theta_w\right)^{10/3}}{\phi^2} \tag{12}$$

where $D_{G_{eff}}$ is the effective diffusion coefficient (m^2/day) for a vapor in soil, and D_G^{air} (m^2/day) is the constituent vapor or gas diffusion coefficient in air. Values for D_G^{air} are available for some of the constituents in the TREECS™ constituent databases, or it can be estimated from molecular weight [14]. The volatilization mass transfer rate is then,

$$K_v = 365\frac{D_{G_{eff}}}{d_v} \tag{13}$$

where d_v is the diffusion layer thickness (m) in the top of the soil layer. By comparing the results of the present model against reported volatilization flux rates, it was possible to determine an appropriate value of about 0.4 m. This relatively simple volatilization model was found

[3] to provide reasonable volatilization flux for widely ranging Henry's constants by using the same diffusion layer thickness of 0.4 m.

After substituting the above defined flux terms and previously introduced relationships for phase concentrations in terms of C_{tt}, the non-solid phase mass balance (Equation 3) can be solved in terms of the unknown C_{tt},

$$\frac{dC_{tt}}{dt} = \frac{F_{dis}}{AZ_b} - \left[\frac{d_e}{Z_b}\left(1-e^{-\kappa}\right)N + \frac{E}{Z_b} + \frac{q_w}{\theta_w Z_b}F_{dp} + \left(\lambda_l F_{dp} + \lambda_a F_{pp}\right) + F_{ap}\frac{K_v}{Z_b} \right] C_{tt} - \frac{F_{precip}}{AZ_b} \tag{14}$$

where F_{pp} and F_{ap} are media concentration conversion factors defined as:

$$F_{pp} = \frac{\rho_b K_d}{\theta_w + \left(\phi - \theta_w\right)K_H + \rho_b K_d} \tag{15}$$

$$F_{ap} = \frac{\left(\phi - \theta_w\right)K_H}{\theta_w + \left(\phi - \theta_w\right)K_H + \rho_b K_d} \tag{16}$$

Equation 14 and Equation 2 constitute a system of two coupled ordinary differential equations that can be solved for the two unknowns, C_{tt} and M_s, which vary over time. The coupling terms are the dissolution and precipitation fluxes. The precipitation flux term in Equations 2 and 14 is zero when solubility is not limiting. After solving the concentration C_{tt}, all of the various flux terms defined above can be calculated for each time point and output as a time series for use as input loads to the vadose zone and surface water models.

A check is required at the end of each time step update to see if the computed value of the soil pore water concentration C_l exceeds the solubility of the constituent in water, C_s. If the computed value of C_l exceeds C_s, then the precipitation flux F_{precip} is computed from:

$$F_{precip} = \frac{AZ_b\left(C_l - C_s\right)}{\Delta t} \tag{17}$$

where Δt is the time step for the most recent time update of the solution. If C_l is less than C_s, then F_{precip} is zero for the next time step update. If pore water concentration C_l exceeds solubility, then precipitation flux computed with Equation 17 is used in Equations 2 and 14 for the solution at the next time step. Equations 2 and 14 are solved using the fourth-order-accurate Runge-Kutta time integration method with an option to use either a constant or variable time step that is automatically adapted to maintain stability.

Vadose Zone and Aquifer Models

The vadose zone and aquifer models, figure 3, are legacy models, and are used in the Multimedia Environmental

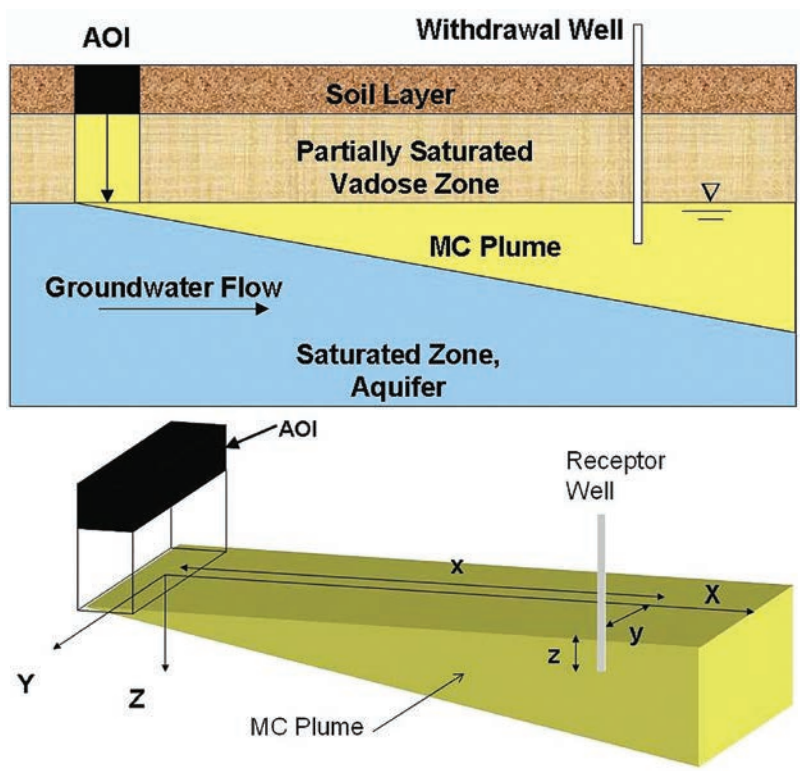

Figure 3: TREECS™ MEPAS Vadose Zone and Aquifer Model

Pollutant Assessment System (MEPAS). MEPAS consists of various models of reduced form for computing multimedia fate and transport, human exposure concentrations, and human receptor doses and health risks [15]. The MEPAS groundwater models consist of time-varying contaminant fate/transport models of the vadose zone and aquifer. The MEPAS version 5.0 groundwater models (http://mepas.pnl.gov/mepas/maqu/index.html) are used within Tier 2 of TREECS™ to compute fluxes through the vadose zone and aquifer and resulting aquifer concentrations at specified well locations. The vadose zone model solves the 1D vertical, reactive transport equation. The aquifer model solves the 1D, reactive, transport equation for longitudinal advection and three-dimensional dispersion. A detailed description of these models is not repeated here since the scientific documentation of the MEPAS groundwater models is provided by [16], and descriptions of both models are provided by [3], [17].

Surface Water Models

Users have two options within TREECS™ Tier 2 for modeling contaminant fate in surface water and sediments: RECOVERY [18], figure 4, and the Contaminant Model for Streams (CMS) [19], figure 5. Both models can be freely downloaded from http://el.erdc.usace.army.mil/products.cfm?Topic=model&Type=watqual. RECOVERY is best suited for pooled surface water, such as ponds and lakes, while CMS is best suited for streams and rivers. These two models are briefly described here since detailed documentation of the models is given in the above references; a more detailed overview of each model is provided within reference [3].

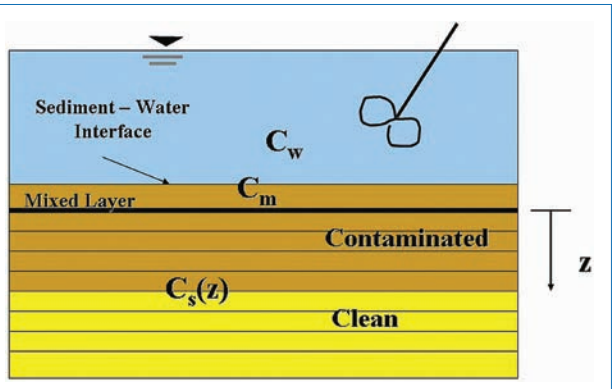

Figure 4: TREECS™ RECOVERY Surface Water Model

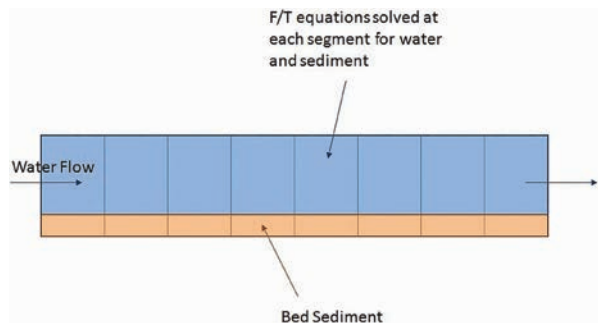

Figure 5: TREECS™ Contaminant Model for Streams Surface Water Model

Both models solve time-varying, mass balance equations for total (dissolved and particulate, i.e., sediment adsorbed) contaminant mass in surface water and bottom sediments with reversible, equilibrium partitioning between dissolved and adsorbed particulate forms. For the RECOVERY model, the water column is treated as a fully mixed single compartment. The bottom sediments are divided into two types: a single, surficial mixed sediment layer at the sediment-water interface, and deep sediment below the surficial mixed layer. The deep sediments consist of multiple layers with each layer 1-cm thick. This treatment results in three mass balance equations with three unknowns, which apply to the water column, the mixed sediment layer, and the deep sediment layers. Two coupled ordinary differential equations are solved for the surface water and the mixed sediment layer. A partial differential equation is solved for the deep sediment layers. The deep sediment extends below the depth of contamination into clean sediment so that a zero concentration gradient boundary condition can be applied at the bottom of the sediment column. Fate processes include: water column flushing, sorption partitioning in the water column and benthic sediments, degradation in water and sediments, volatilization from water, water column sediment settling and bottom sediment resuspension, deep sediment burial, mass transfer of dissolved constituent between the water column and mixed sediment layer pore water, bioturbation between the mixed sediment layer and top layer of the deep sediments, and pore water diffusion within the deep sediments. Loading boundary conditions include inflowing contaminant mass due to export from the soil model, which includes rainfall extraction, erosion, and soil interflow fluxes. There is also an option to enter user-specified constant external loadings of contaminant

mass, such as those due to wastewater discharges, air deposition, or stream background loadings. Although the dependent variable is total concentration, the model produces output for total and dissolved concentrations in the water column and bed.

The CMS is very similar to RECOVERY with the primary difference being the dimensionality and its orientation. CMS treats the water column as 1D in the longitudinal or stream-wise direction, thus representing contaminant fate and transport in streams and rivers. Only a single, fully mixed compartment is used to represent the benthic sediments underneath each 1D water cell. There is exchange between the sediment compartment and the overlying water just as in RECOVERY, but there is no longitudinal exchange between benthic sediment compartments except for that associated with surface water fate and transport. The model solves a partial differential equation for the 1D, advection-diffusion-reaction (mass balance) equation of the surface water cells and an ordinary differential equation for each benthic sediment compartment. The CMS assumes steady, uniform flow. Stream flow can vary over time, but there is no hydraulic or hydrologic routing involved. There are various options for estimating the flow cross-sectional area and depth based on flow rate. The modeled fate processes are the same as those in RECOVERY, except that bioturbation is not included since there is only one benthic layer. CMS has been verified against analytical solutions and RECOVERY [19].

Model Linkages

The exchange of model outputs that are used as inputs to down-gradient models, such as soil export to vadose zone and surface water, are handled within TREECS™ via the file specification system used in the Framework for Risk Analysis in Multimedia Environmental Systems (FRAMES), [20]. Several federal agencies use FRAMES to facilitate multimedia environmental modeling.

For worst-case conservatism, mass fluxes exported from the soil to the target surface water are transferred directly without attenuation, transport time delay, or mass loss. Thus, if the target surface water is a pond downstream of a range, and the stream connecting the range to the pond is not part of the surface water model, then mass fluxes from the range become input mass loadings to the pond without alteration in route through the connecting stream.

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Authors' Biographies

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Dr. Billy E. Johnson received his B.S. in Civil Engineering from Mississippi State University (1987), his M.S. in Civil Engineering from Memphis State University (1993), and his Ph.D. in Civil Engineering from Colorado State University (1997). He works for the U.S. Army Corps of Engineers at the Engineer Research and Development Center and has 25+ years of experience in Water Resources. He works in the Environmental Laboratory's Environmental Modeling Branch. Dr. Johnson is the leader of the Watershed Water Quality Modeling Group which develops nutrient and contaminant modules for linkage and integration within a number of USACE Hydraulic and Hydrologic modeling systems. His group developed the Training Range Environmental Evaluation and Characterization System that is currently being tested and applied for the Operational Range Assessment Program (ORAP) Phase II. Dr. Johnson is an adjunct faculty member of the Civil and Environmental Engineering Department at Mississippi State University where he teaches Engineering Hydrology and Environmental Hydrology. Dr. Johnson is a member of multiple technical societies and is an associate editor for Surface Water Hydrology for the *Journal of the American Water Resources Association* (JAWRA).

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Impact Simulations for the Small Unmanned Ground Vehicle (SUGV)

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Abstract

THE U.S. ARMY MATERIEL SYSTEMS ANALYSIS ACTIVITY (AMSAA) SUPPORTED PRODUCT MANAGER UNMANNED GROUND VEHICLES (PDM UGV) BY DEVELOPING A FULL SYSTEM FINITE-ELEMENT MODEL OF THE SMALL UNMANNED GROUND VEHICLE (SUGV) FOR IMPACT SIMULATIONS. BY DROPPING THE SUGV IN A VIRTUAL ENVIRONMENT, AMSAA EVALUATED THE EFFECTS FOR A TOP-ORIENTED IMPACT WITH AN ALTERNATE PAYLOAD CONFIGURATION AND A SIDE-ORIENTED IMPACT, WHICH CAUSED AN OBSERVED TEST FAILURE. THE TOP-ORIENTED IMPACT SIMULATIONS EXPOSED A POTENTIAL DESIGN RISK AND EVENTUALLY SUPPORTED THE EFFECTIVENESS OF THE CONTRACTORS MODIFIED DESIGN PROPOSAL. THE SIDE-IMPACT ANALYSIS, IN CONJUNCTION WITH TESTING, ENABLED THE CONTRACTOR AND GOVERNMENT ENGINEERS TO DETERMINE THE ROOT CAUSE OF AN OBSERVED FAILURE, VISUALIZE THE LOADING AND UNLOADING DURING IMPACT, AND TO EVALUATE THE EFFECTIVENESS OF THE PROPOSED CORRECTIVE ACTIONS. IN BOTH CASES, THE MODELING AND SIMULATION (M&S) EFFORTS POSITIVELY IMPACTED THE DESIGN AND POTENTIALLY SAVED THE GOVERNMENT MILLIONS OF DOLLARS BY HELPING TO VALIDATE RELIABILITY IMPROVEMENTS OF THE SUGV BEFORE FIELDING THE SYSTEM.

Introduction

The Small Unmanned Ground Vehicle (SUGV) "is a lightweight, Soldier-portable Unmanned Ground Vehicle (UGV) capable of conducting military operations in urban terrain, tunnels, sewers, and caves. The SUGV aids in the performance of urban Intelligence, Surveillance, and Reconnaissance (ISR) missions, chemical/Toxic Industrial Chemicals (TIC), Toxic Industrial Materials (TIM), reconnaissance [1]." iRobot developed the SUGV through cooperation with the Brigade Combat Team (BCT) Modernization Program, which is now managed by PEO Ground Combat Systems (PEO GCS).

The successful integration of the SUGV into BCTs limits Soldiers' exposure to the enemy and limits direct contact with hazards, potentially saving lives. The SUGV is maneuvered over rock piles and through tunnels, sewers, and caves. The potential encounters with drop-offs of substantial heights, leads to demanding vibration and drop impact requirements. Tools are available to assist in meeting the requirements. Physical drop tests can be performed but require sophisticated instrumentation and high-speed cameras, and the exact orientation at impact is difficult to control. M&S provides a way of capturing similar (and additional) data to physical test but potentially cheaper and without the need for a physical test asset. Furthermore, modeling and simulation (M&S) enables engineers to perform *what-if* scenarios (for instance, what if the SUGV had a twelve-inch mechanical arm as a

payload), conduct root cause analyses, estimate the effects of material or component changes (simply and quickly), and observe/measure (quantify) impact behavior.

M&S of impact simulations requires the use of Finite Element Analysis (FEA). There are many commercially available software codes that enable analysts to effectively simulate short duration, high energy events. Impact simulations typically use an explicit time integration scheme which is well suited to solve problems with high energy and deformation over very short time durations. For this system, an impact event from a 2m drop height lasts milliseconds while causing accelerations of several hundred g's. AMSAA analysts used the Abaqus/Explicit solver available within the Abaqus software package to develop a system level model. Abaqus is a Commercial Off-The Shelf (COTS) FEA package which includes the capability to model non-linear material behavior and high energy impact events. From the software vendor's website:

> Abaqus/Explicit is a finite element analysis product that is particularly well-suited to simulate brief transient dynamic events such as consumer electronics drop testing, automotive crashworthiness, and ballistic impact [2].

This capability makes the Abauqs software package an ideal tool for simulating the impact from a drop test event.

The model allowed engineers to simulate impact events from various drop heights and orientations in a controlled manner before or in conjunction with conducting physical tests. For example, visualizing and understanding the load path and energy management are not easily accomplished in a physical test event, but are standard outputs attained through simulation. Although the drop requirement only specifies PASS/FAIL type testing for three defined orientations, PdM UGV and iRobot recognized the risk to the system from uncertainty with respect to other impact orientations and drop heights. Because of this foresight, the AMSAA developed model was available and could support two alternate events: a top impact with payload and side impact event which required analyses during the period before and directly after a high-visibility customer Critical Design Review (CDR). M&S allowed analysts to evaluate impacts from different orientations and system configurations. In cases when testing produced an observed failure, M&S allowed engineers to understand the root cause of the failure by supplementing future testing with load path information which the simulations could confirm.

Finite Element Model Development

The large computational requirement, inherent when performing impact simulation, necessitated a model constructed of fully detailed components, realistically approximated components, simplified components, lumped masses, and idealized connections. Even with access to the High Performance Computing (HPC) resources at the Army Research Lab (ARL), the simulations could take up to 8 hours. These modeling techniques are common practices when developing finite element models, but were critical for a system level model because of the conflicting requirements for a model that can replicate the physical test but also run efficiently and deliver results in a timely manner.

The full system model development involved many sub-modeling efforts because fully detailed representation of all parts is not practical with regards to model solve time. The analyst must efficiently characterize the physical components with computationally efficient representations accurately capturing the physical deformation during the impact. Examples of this method include the main wheels and track, which if modeled in full detail would make conducting a series of alternate scenario analyses or meeting time sensitive deadlines impossible. The model allows for substitution of the full detailed parts in lieu of the simplified parts if more accuracy is required after the initial analysis.

The Flipper sub-assembly, visible in figure 1, illustrates the level of complexity that the finite element software can model. The flipper consists of many parts modeled at various levels of detail. The procedure for modeling the flipper sub assembly was typical of the analyst's approach when modeling other parts of the SUGV. Because the software offers many ways to model the same part, and analysts must balance computational time and accuracy concerns, judgment and experience play a significant role in the model development. In the flipper, some parts

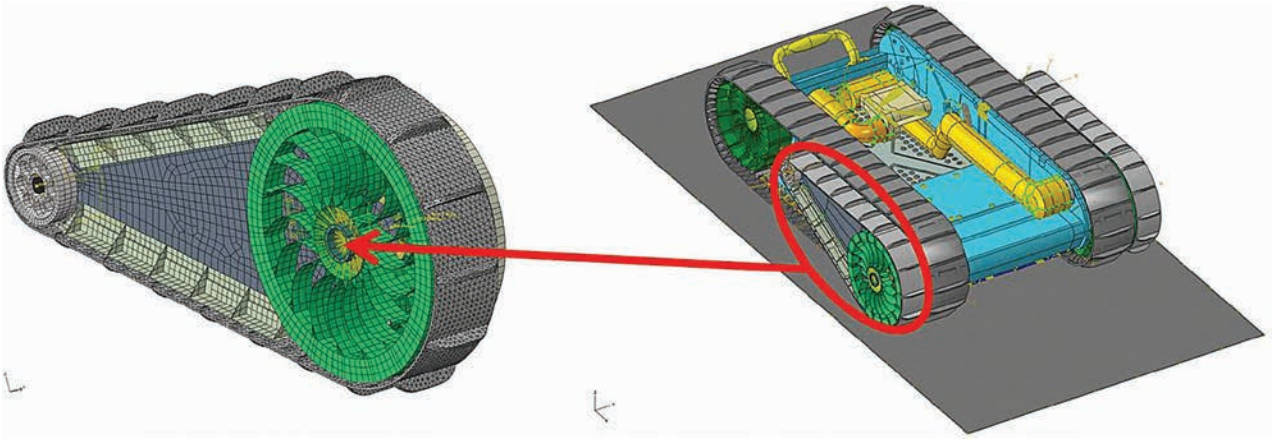

Figure 1: Full SUGV model and component detail example

such as the tip wheels utilize full detail solid elements. The track, main flipper body and the flipper wheels were shell approximations that closely matched the stiffness and deformation behavior of a full detail solid part before inclusion in the model. Idealized connector elements and coupling constraints represent the connections between parts. The model allows contact between all parts.

Capturing the wheel and track model deformation accurately is of paramount importance for accurate and usable model results. Figure 2 shows visual confirmation that the wheel deformation and impact behavior match the intended behavior of the prototype wheel. The simulation replicated a test of a prototype wheel and spoke design. Engineers expected some difference because the prototype wheel was not identical to the simulated wheel, but the deformed shapes are very similar. In this case, the simulation was conducted before knowing the deformed shape, and the image in figure 2 provides a visual comparison, but was not an *apples-to-apples* comparison. For the full system, high speed video enabled engineers to determine if the simulations had similar impact durations and rebound velocities to the physical tests; however, the initial visual comparison proved to be a valuable screening tool when determining if the model matched the test.

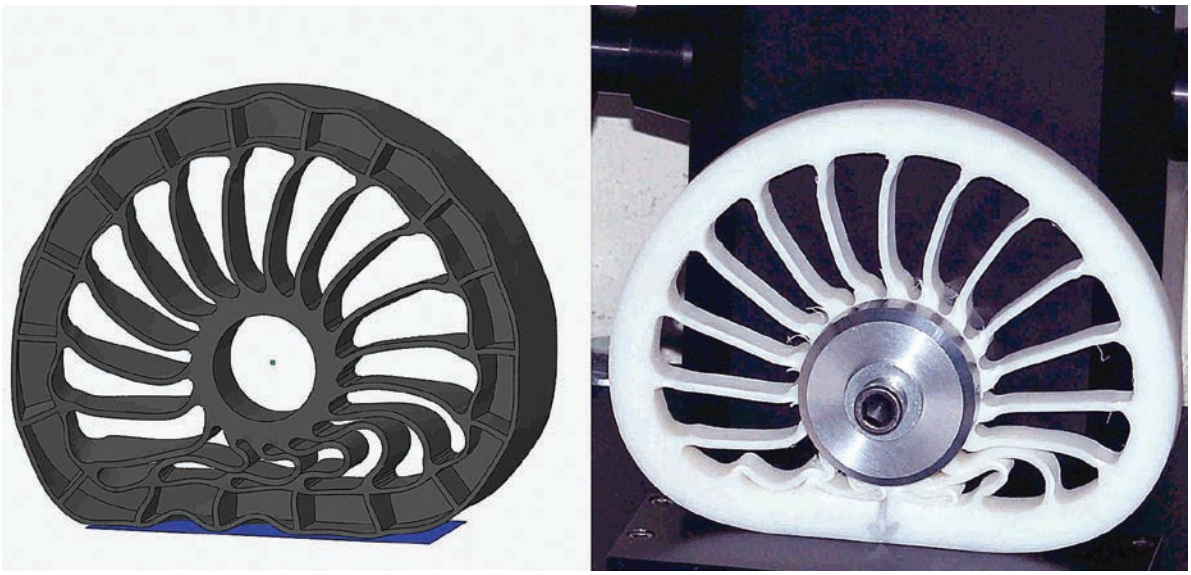

Figure 2: Wheel Deformation Comparison: Model (Left) vs. Prototype Wheel (Right)

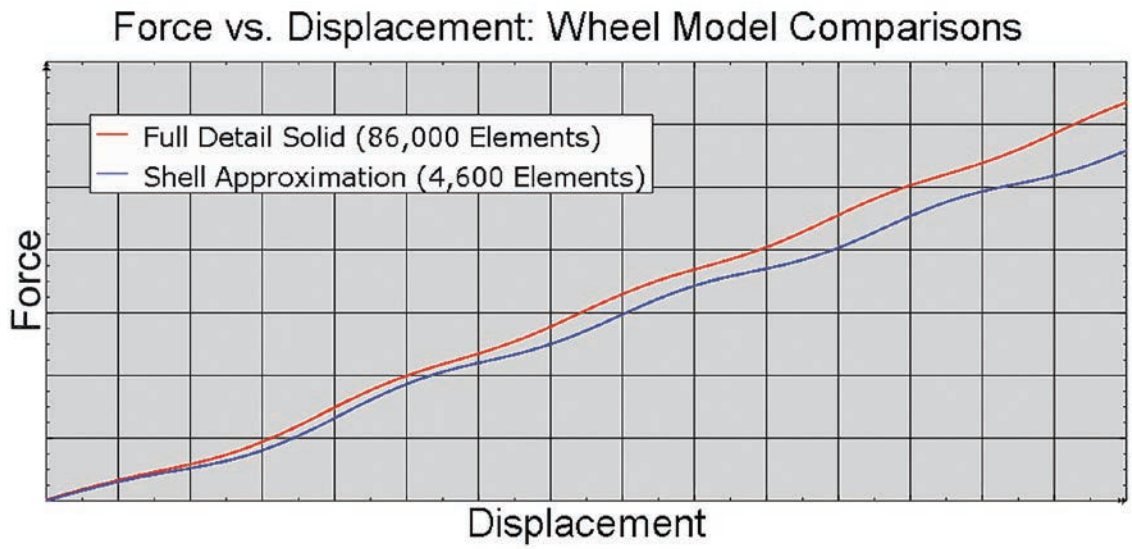

Figure 3: Force vs. Displacement curves between full solid and simplified shell models.

For many parts, computation time constraints require one additional level of abstraction. As previously stated fully detailed meshed parts are impractical. Figure 3 shows the difference in force vs. displacement curves between a solid model and shell approximation model for the main wheels. The simplification provides a substantial computational savings with only a small cost in accuracy at the largest material deformations. The simplification allowed AMSAA to provided analysis results within the desired time constraints with minimal loss of solution accuracy.

For many components, data for a complete material property characterization is not available. Most commercially available software packages include a wide variety of robust verified material models. The Abaqus Verification Manual demonstrates the capability of the various material models to match measured test data under different loading conditions, including uniaxial tension and compression, planar shear, and biaxial tension [3]. According to the course notes from the Abaqus training on modeling hyperelasic materials [4] and Axel Products, Inc., a private company that specializes in characterizing hyperelastic materials for use in FEA, [5] the actual properties required to fully utilize the material models require extensive testing.

In many cases limited data are enough to characterize part of the material behavior. For example, data are not available to characterize the extreme range of extension for a hyperelastic material, but a few stress-strain points produce a stable and accurate representation of the initial hyperelastic stress-strain relationship. If the known operating range of the part falls within this region the material model may provide accurate results even though the FEA representation of the part only incorporates a first order material model. Many material suppliers provide limited data for commercially available materials. In some cases the limited data are enough to provide an acceptable material behavior in the model. Abaqus includes a tool to calibrate material models to test data. The analysts must choose the best fit for the strain range of interest. Some material data was robust enough to use a higher order material model. Figure 4 shows the stress-strain relationship for a single element FEA calibration model versus the supplied material data. For this material, the FEA material model provides a close match using the Yeoh material model, which is a 3rd order reduced polynomial model. The Abauqs Theory Manual [6] includes details on the available material models.

For the wheels, material properties published by the material supplier produced acceptable results when calibrated with a single solid (hex) element model. Not all available material data produces such successful results. AMSAA

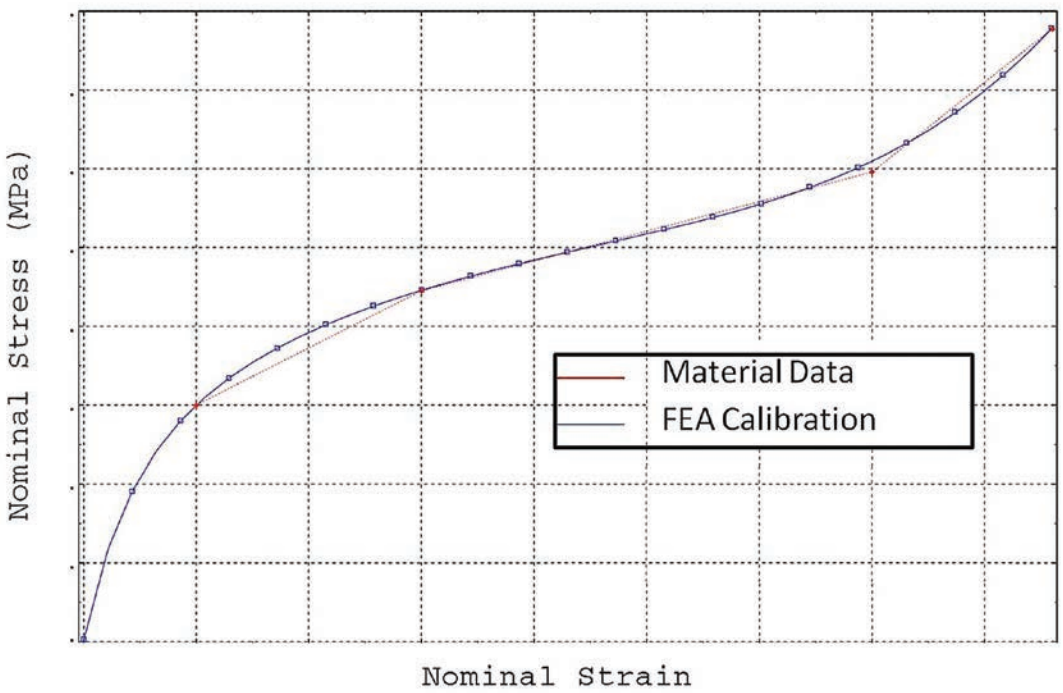

Figure 4: Example of Material Calibration Model Results

used this SUGV model as a comparative tool to augment physical testing and internal analyses conducted by the manufacturer. With that intended use in mind, analysts attempted to match material behavior against available data; more comprehensive material testing could be conducted at a later date, if required.

The main wheels are only one illustration of the model development process where analysts must represent the physical system with varying levels of fidelity to balance the competing project requirement. The chassis is another example where the initial effort to simplify the modeled representation while maintaining the correct behavior during impact saved 1000's of computation hours. These simplifications allowed AMSAA to provide timely and relevant results that impacted the design. The Abaqus software includes connector elements that enable analysts to model complex behaviors with built in behavior templates. The Abaqus User's Manual [7] provides definitions of the different behaviors available when using a connector element. They are particularly useful because an analyst can create connections between parts ranging from simple rigid connectors to complex joints. These were particularly useful for defining the joints and fasteners present in the SUGV, which included joints with elastic, friction, and damping properties. A complete list of available behaviors is available in the manual. As with other component abstractions, analysts must verify that the idealized behavior is an acceptable representation of the physical system. Analyst experience and careful reading and understanding of the software's capabilities are important.

The final stages in model development are verification and validation. Analysts referred to the Army's guidelines for verification and validation [8]. Careful model construction should ensure that the model meets the verification requirements, in the sense that the components modeled accurately represent the physical system. In addition, some of the techniques outlined by Chung & Kahre [9] can help analysts ensure that the model is error free. Validation against limited test data produces mixed results. In general the model over-predicts the accelerations on the chassis; however, visual validation of the simulation with high-speed video from tests reveals that the behavior of the SUGV during impact events appears correct.

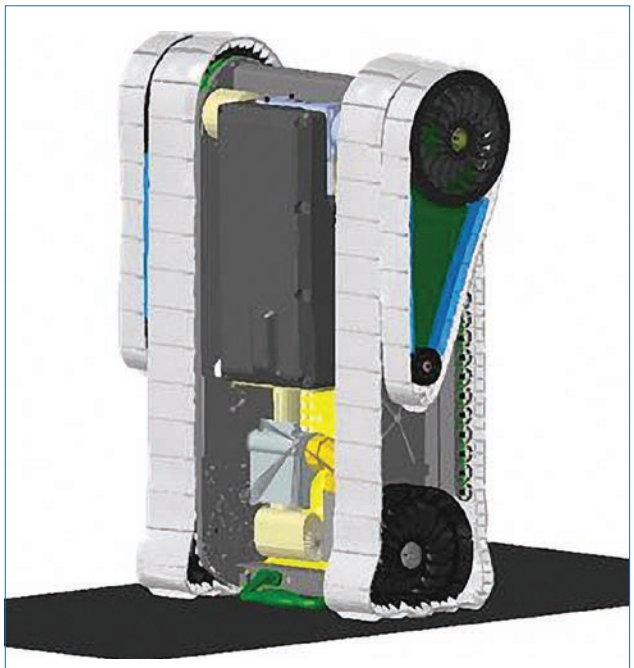

Figure 5: Tail Impact (Global View)

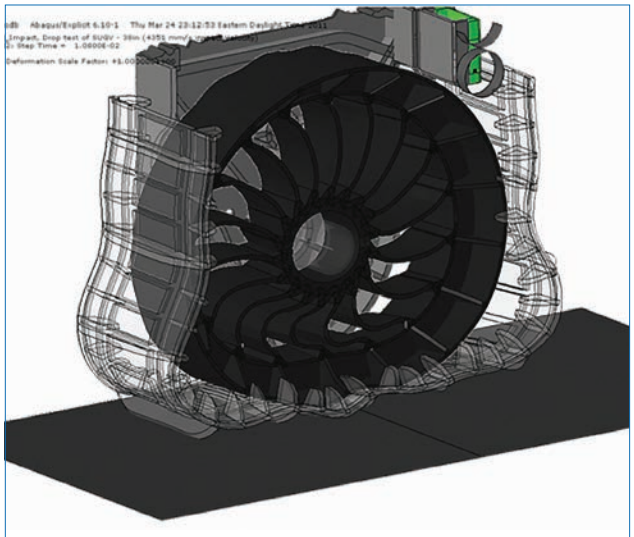

Figure 6: Tail Impact: Wheel (Local View)

The images in figure 5 and figure 6 show the simulated deformation during a tail impact. These images agree with still images from test video. During the initial comparisons between simulations and tests, Engineers from AMSAA and iRobot determined that the track to ground contact interaction as well as the track material properties during high strains rate were the largest source of error. There are two corrections which should improve the track behavior within the model, leading to a more accurate simulation (reduced error between simulation and test). First, the physical track has some level of track tension which varies depending on the age of the track and material used. The model has essentially zero track tension. Importing a pre-stressed version of the track should improve the track performance during impact; track tension has a known role in system mobility performance and is believed to play a role in impact as well. Second, improving the track model fidelity within the impact region should improve the model simulation results. Adding a full solid geometry meshed region of the track in the impact region should allow for a more accurate energy transfer as the track grouser tabs compress and flex.

Another significant contributor to error is the difference in ground surface representation between the model and previous tests. The model uses a rigid ground surface; whereas, the tests incorporated multiple sheets of plywood. The use of a rigid impact surface is a common simulation practice in impact analyses. The plywood construction, shape, base material, and bonding matrix are unknowns and provide a significant source of model error when estimated. The observed curvature of the plywood pieces during the physical tests would be difficult to capture without very detailed measurements, which were not made at the time of the test. The rigid ground provides a more severe impact than the stacked plywood. While future efforts may include attempts to incorporate the plywood, or represent the effects of the plywood ground surface, AMSAA and iRobot engineers agreed that the rigid ground simulation provides the *worst case* impact scenario. With this understanding, AMSAA could use the model to provide an upper bound on the impact as well as conduct A to B comparisons.

Payload Top Impact

The SUGV is capable of carrying a payload mounted on the top of the system. Although a top impact is not a requirement, all interested parties realized that a top impact on a payload extending beyond the base SUGV (i.e., the payload impacts the ground instead of the SUGV track and wheels) presents a significant risk to the system. The addition of the payload reduces the survivability of the overall system, but the limitations with respect

to drop height are not easily obtained without analysis. In coordination with ongoing testing conducted by the payload supplier, Raytheon, AMSAA used the full system model of the SUGV with the payload as well as a simplified model replicating the on-going testing to assist with the analysis of the top drop with payload. AMSAA used M&S to evaluate the top impact with the payload mounted on a physical chassis. Due to the potential damage to limited chassis assets, engineers had not conducted physical testing of a full system with payload top impact. The results in figure 7 provided engineers from the SUGV supplier, payload supplier, and government with confidence that full system impact simulations would provide meaningful results.

One crucial discovery from the full system M&S was a potential catastrophic failure caused by contact between the payload and SUGV chassis. A protective foam layer covered the payload top to help mitigate the impact energy. For this analysis effort, accurately modeling the foam material negated the error causing effects of the ground surface because the foam is significantly more compliant than the SUGV track and wheels. More importantly, the track-to-ground interaction does not affect the results. The Payload supplier had conducted testing using a surrogate mass in place of the actual SUGV chassis. The test involved dropping the surrogate mass and payload on a foam pad while measuring the acceleration experienced by the payload. The chart in figure 7 shows the simulation vs. test comparison. Explicit simulation results can be very noisy by virtue of the small stable time increment required [6]. Time increments for the SUGV model were on the order of 8E-8s (12.5MHz sample rate) using a negligible amount of mass scaling. Post processing these results requires some knowledge of Digital Signal Processing (DSP) [10]. This article does not include a complete description of DSP techniques used, but a systematic approach to DSP enabled the analysts to present meaningful results when the raw time history output from the model contained excessive simulation noise, which masked the true response.

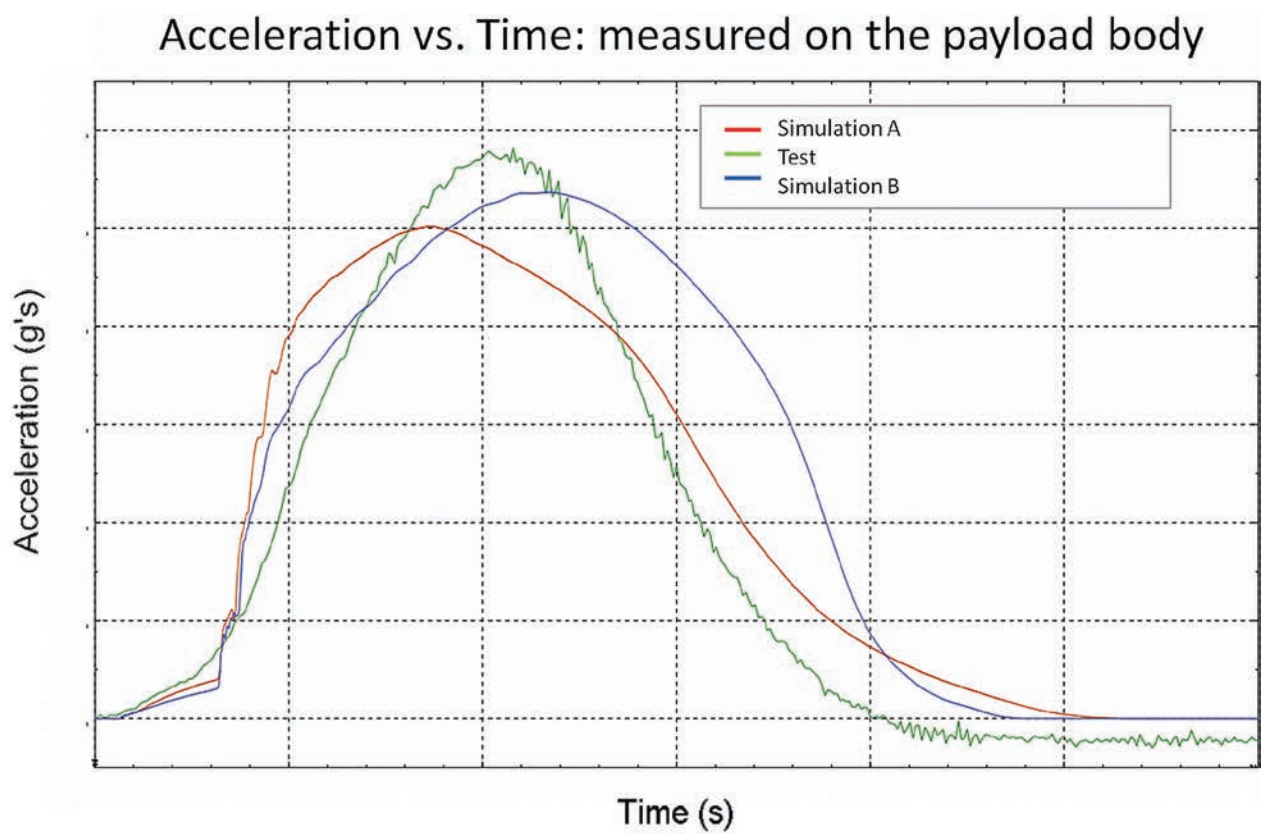

Figure 7: Top drop Acceleration vs. Time: Test & models

The material manufacturer provided a quasi-static compressive stress–strain curve which AMSAA used with the Low Density Foam [7] material model available within Abaqus. With feedback from the material supplier, AMSAA approximated the rate dependent effects and augmented the available test data with rate dependent loading curves. Actual rate dependent data were not available, but the simulation results produced peak accelerations within 5 percent of the test results.

The results depicted in figure 8 were the product of cooperation between government and both contractors (Raytheon and iRobot). After the analysis uncovered the potential risk, AMSAA implemented numerous conceptual changes to the payload and chassis interaction region. These changes were the product of brainstorming during discussions with contractor and government engineers. The final product sees significantly lower stresses and negligible contact between the payload and unreinforced regions on the SUGV chassis.

The design modification illustrates the potential for effective M&S. Even with known deficiencies (material property definitions), the model averted potential failures in both test and fielded assets before conducting a single full system level test with the payload. Additional M&S assisted engineers to determine the best configuration by illustrating the effectiveness of load path management enabling the design to most efficiently absorb the energy from impact without damaging the chassis. Catastrophic damage to one of the limited test asset systems would result in a replacement cost and test schedule delay costs.

Side Impact Analysis

After performing physical drop testing with the SUGV positioned for a side impact, iRobot engineers discovered cracks in the chassis and the small wheels on the flipper tips. iRobot engineers outlined a series of design modifications to alleviate the problem. The working hypothesis was that during a side impact, when the flipper tip wheel contacts the ground first, all of the energy transfer occurs through the interaction with the relatively stiff and brittle flipper tip wheel and a battery bulkhead attached to the main SUGV chassis.

Figure 8: Chassis Stress: Original (Top) and Modified (Bottom)

Engineers believed that changing the flipper tip wheel design to allow increased deformation during loading along with reinforcing the chassis will improve the energy transfer during impact and eliminate the cracks. Figure 9 depicts the observed failure locations resulting from a side impact.

Because the AMSAA developed model can be readily changed to accommodate component replacements and various impact orientations, PdM UGV tasked AMSAA

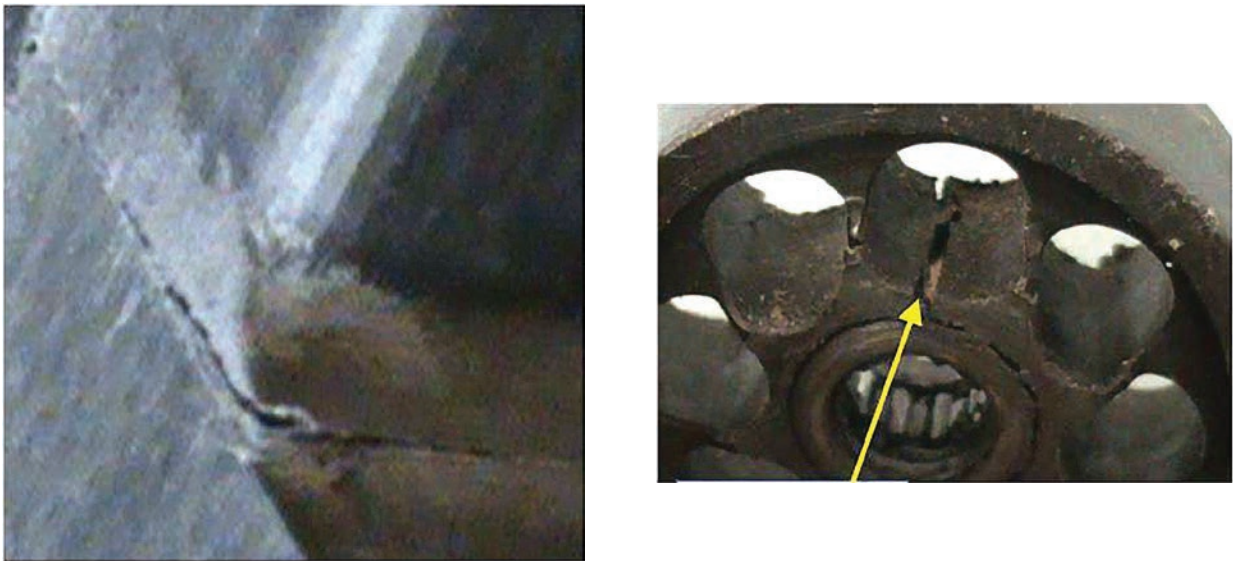

Figure 9: Failure locations after side impact

to support the analysis of the modifications with M&S using the full system SUGV FEA model. By working with iRobot engineers, AMSAA modified the original model to include the redesigned flipper and flipper tip wheels and performed analyses based on the observed configuration and impact orientations from test.

The wheel deformation behavior, shown in figure 10, of the modified flipper tip wheel correlated well between the model and the test. As with previous analyses the physical stacked plywood impact surface helped dissipate some of the energy during impact. The finite-element model, impacting a rigid ground surface, represents the worst case and reported chassis accelerations that are nearly 40 percent higher than those measured in the test; however, engineers from both the government and iRobot agreed that the model represented the *worst case* and the impact behavior and deformation matched the test. The tests with the modified flipper wheel design did not produce any failures, but two questions arose that the model could answer more definitively and cost efficiently than a test:

1. What impact orientation causes the highest loads on the chassis?
2. What are the contact forces generated on the battery bulkhead during impact?

AMSAA used the full system model with four different impact orientations to answer the first question. The model confirmed that the highest stress on the chassis occurred during a flipper tip wheel impact. The stresses for the scenario where the SUGV impact orientation allowed the tip wheel to absorb most of the impact force were higher than the cases where the rear wheel, front wheel and front wheel axle (perfectly parallel to ground impact) absorbed most of the impact.

To answer the second question more quickly AMSAA replaced everything but the rear wheel, battery bulkhead, and the flipper with an equivalent lumped mass and inertia. This simplified

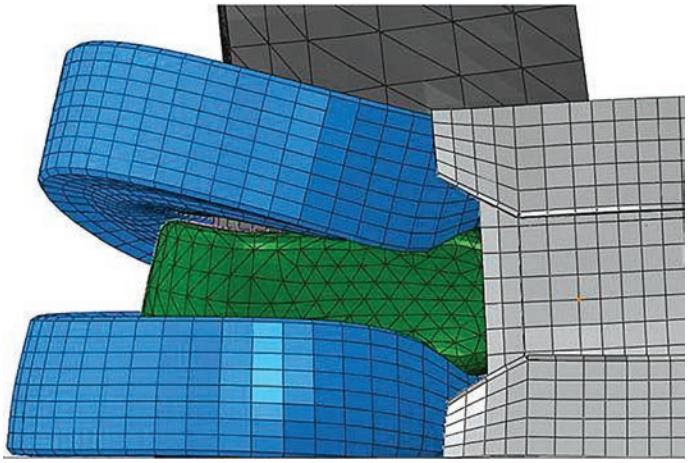

Figure 10: Flipper Tip Wheel deformation during impact

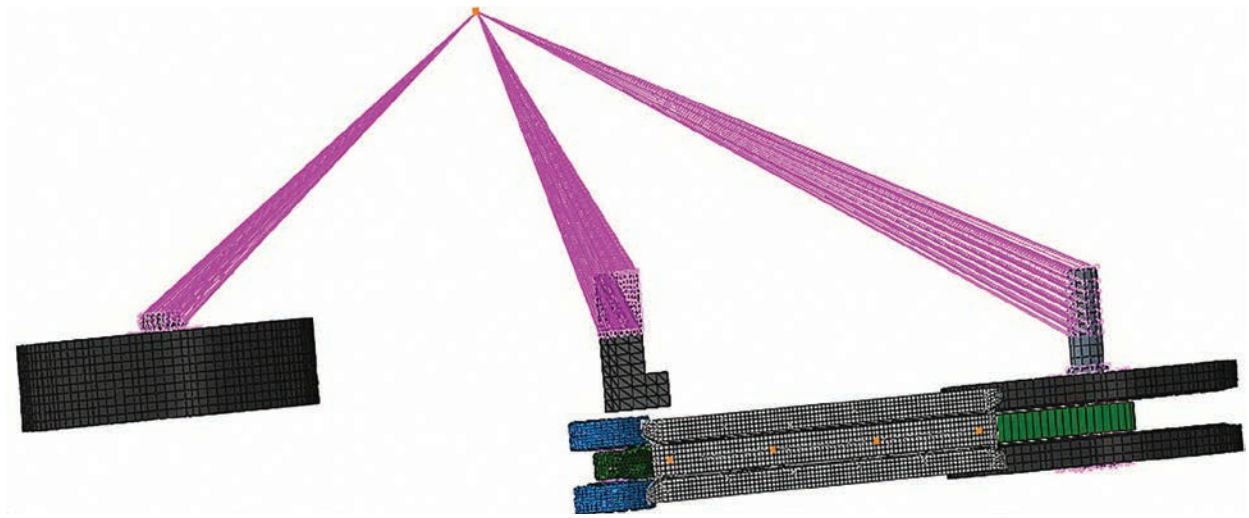

Figure 11: Simplified Flipper Impact Model

model, shown in figure 11, allowed analysts to run many impact scenarios with different impact angles and flipper positions while still approximating the real world conditions outside of the area of interest. AMSAA used the full model to report final results, but initial screening using the simplified model helped produce results within the time constraints.

The simulation results confirmed that the modified flipper wheels provided better energy management. The contact force between the flipper tip wheel and the battery bulkhead is reduced and the force is applied more slowly and over a longer duration. This is clearly shown in figure 12. Not depicted on the chart are the front wheel contact forces. By allowing more deflection and slowing the rate of impact, the modified flipper tip wheel design allows the front wheel to contact the ground and share some of the impact force as opposed to transferring most of the force through the battery bulkhead during impact.

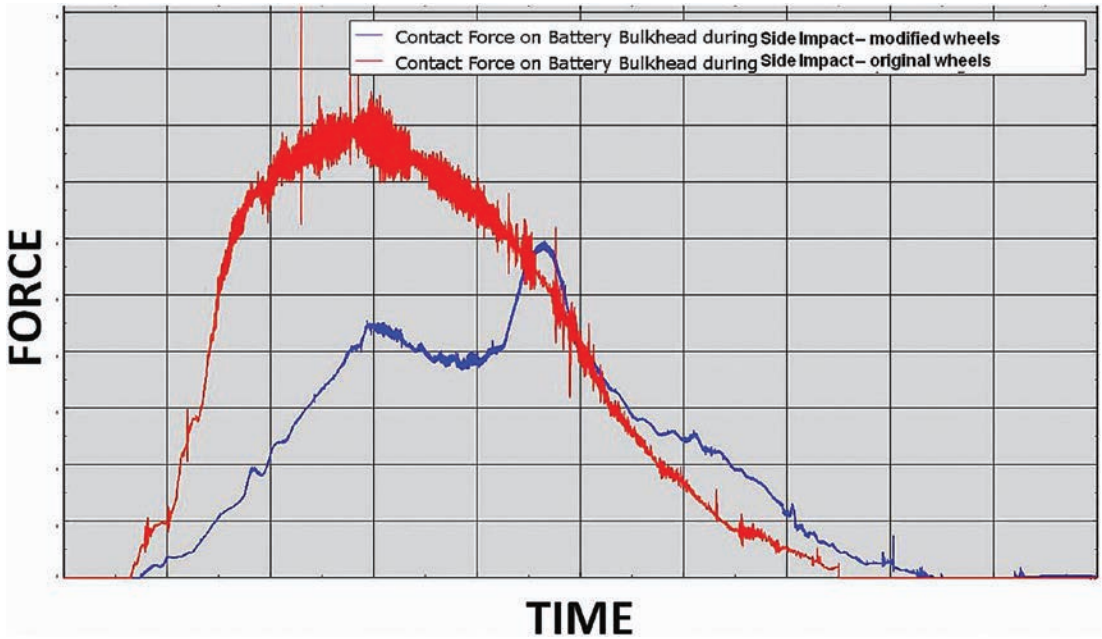

Figure 12: Flipper Wheel Contact Force vs. Time

Conclusion

The results from these two analyses led to design changes that helped to improve the SUGV system reliability. By developing models early in the program's life, which were used to help improve and inform design decisions, PdM UGV potentially saved millions in future costs. A rough order of magnitude estimate is that a 20 percent improvement in reliability could save over $9 million in future cost. For the specific cases outlined in this report, the use of M&S helped prevent catastrophic damage to the chassis. The payload top drop would have resulted in damage to the chassis and possibly created a puncture exposing the sensitive electronics components. Damage to the chassis is not easily reparable and most likely requires the purchase of a new system, and at best, results in reduced system availability. The side impact resulting in a chassis crack and broken flipper wheel would yield similar cost increases and availability reductions.

M&S, in conjunction with testing, assists decision makers by providing increased confidence through a greater understanding of system behavior and the consequences of that behavior, and by augmenting testing with additional information not always available or easily attained. M&S cannot replace the physical tests, but effective M&S significantly reduces risks and saves time and money. M&S enables the managers to allocate test assets more effectively (e.g., predict the worst-case drop orientation or identify areas of concern that should be instrumented) and can provide additional pieces of information such as predicting the loads within a latch that cannot be instrumented. The use of unmanned systems provides soldiers with increased standoff distance, improved situational awareness and potentially saves lives. System reliability and availability are of critical importance, and M&S can help improve those systems which are vital to the soldier.

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