Development of a Digital Simulation Supporting the US Space Force National Test and Training Complex

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ABSTRACT

The United States Space Force (USSF) was signed into law as part of the 2020 National Defense Authorization Act in recognition that our competitors and adversaries have turned space into a warfighting domain. Potential adversaries recognize the advantage the US gains by operating in space. They are responding, fielding their own systems to exploit the domain which may put US space systems at risk as attempts are made to deny US use of space. Accordingly, the Defense Space Strategy identifies a phased approach to encourage innovative and bold actions to ensure US space superiority. Given the challenging and costly nature of testing in space, simulation may be the best option available to enable the USSF to characterize the complex, system-of-systems (SoS) environment, while mitigating costs and protecting sensitive mission capabilities that may be revealed by on-orbit testing. The USSF is developing the National Space Test and Training Complex (NSTTC) to provide critical infrastructure to enable operationally relevant test and training of all-domain, SoS capabilities that form the enterprise response to increasingly sophisticated adversary capabilities and tactics. This paper will concentrate on the development of the digital simulation environment (aka the NSTTC-D). Specifically, the authors will discuss how the NSTTC-D team is successfully leveraging test and training Mission Engineering and Model Based Systems Engineering to inform a scaled agile development process based heavily on software and model reuse. As such, the NSTTC-D team will collaborate with the modeling and simulation community from a multi-service, industry, and academia perspective. The reader should be provided with an understanding and appreciation for the NSTTC-D's test and training initiatives, tailored simulation processes/challenges, and path forward leveraging simulation as part of its vision to provide space warfighters with a digital venue to develop, validate, and sharpen joint warfighting solutions.

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INTRODUCTION

Access to space-based capabilities has become an essential part of military operations and an expected part of everyday life for people around the globe. There was a time when the race for space dominance was a competition between the United States and the former Soviet Union. Clearly, this is no longer the case, with many more nations and companies vying for a controlling share of this ever-expanding technological domain. Space capabilities have become central to military operations worldwide, including missile warning, geolocation and navigation, target identification, and tracking of adversarial activities. Historically, these capabilities have afforded the United States and its allies with tremendous technological advantages. Having seen these benefits, other nations have taken steps to challenge and counter those advantages. As stated in the Defense Intelligence Agency's (DIA) 2019 report, "Challenges to Security in Space", Chinese and Russian military doctrines indicate they view space as important to modern warfare and view counterspace capabilities as a means to reduce US and allied military effectiveness. Recognizing the threats to our critical space-based assets and the need to provide defensive capabilities the United States Space Force (USSF) was created on 20 December 2019 through the Fiscal Year (FY) 2020 National Defense Authorization Act.

The Defense Space Strategy identifies a phased approach to encourage innovative and bold actions to ensure US space superiority. Given the challenging and costly nature of testing in space, simulation may be the best option available to enable the USSF to characterize the complex, system-of-systems (SoS) environment, while mitigating costs and protecting sensitive mission capabilities that may be revealed by on-orbit testing. The USSF requires critical infrastructure to enable operationally relevant test and training of all-domain, SoS capabilities that form the enterprise response to increasingly sophisticated adversary capabilities and tactics. The National Space Test and Training Complex (NSTTC) is the reply to that call to action.

NSTTC and the Digital Range

In January 2023 General B. Chance Saltzman, Chief of Space Operations, communicated three lines of effort (LOE) (United States Space Force News, 2023):

- LOE 1. Field Combat-Ready Forces
- LOE 2. Amplify the Guardian Spirit
- LOE 3. Partner to Win

The first LOE, Field Combat-Ready Forces, contains five guiding principles, of which two have significance to the USSF's NSTTC program. Force design and resourcing recommendations must be "fully burdened" to incorporate crew force requirements, command and control, intelligence, networks, cyber defense, test and training infrastructure, sustainment, and facilities. The USSF must have range capacity and representative training devices capable of preparing Guardians to engage a thinking adversary in a realistic threat environment. Operational concepts and tactics must be continuously developed, assessed, and enhanced through a service-wide campaign of learning, led by the units entrusted with our systems. The second LOE, Amplify the Guardian Spirit, includes the need for Guardians to have a deep understanding of space operations and be experts in deploying space capabilities against an adversary. The third LOE, Partner to Win, points out that space power is already a collaborative endeavor and that the USSF will not succeed without robust joint, coalition, international, interagency, academic, and commercial partnerships.

Executing these LOEs the NSTTC system concept aims to provide critical capabilities and infrastructure to enable operationally relevant test and training of all-domain space System of Systems (SoS) capabilities. Major General Shawn Bratton, Commander, Space Training and Readiness Command (STARCOM) established a vision for the NSTTC to provide space warfighters interconnected, scalable, and distributed physical and digital ranges to develop, validate, and sharpen joint warfighting solutions for full-spectrum test and training to prevail in conflict (USSF STARCOM, 2022). To accomplish this vision, the NSTTC will be developed with distinct service capabilities that operate in concert to develop, implement, and execute the NSTTC's operations. These capabilities include a Digital Range, Orbital Range, Electromagnetic Range, Cyber Range, and a Special Projects LOE. This paper is focused on the NSTTC Digital Range (NSTTC-D).

Development of a Digital Simulation Range for Space

The NSTTC-D will provide the central element of the digital range providing a structured, standardized, and process-controlled computational environment to which System Program Offices (SPOs) to bring the high-fidelity models and simulations they have developed to test, train, and assess in the SoS space enterprise. This digital venue will be a flexible, extensible environment supporting the agile development of emerging capabilities while providing the high run counts needed to establish statistically significant performance assessments that cannot be achieved by orbital tests alone. The digital simulation environment also provides the ability to explore defensive capabilities without exposing them to a watchful adversary, as would be the case for live, on-orbit tests. To accomplish these objectives the USSF will develop a Minimum Viable Product (MVP) during its first developmental increment, over the course of FY23-24. Upon completion of the MVP the NSTTC-D will be comprised of a flexible and robust simulation framework focused on a demonstrative performance assessment for a limited number of classified and unclassified mission threads. Future increments are undefined but may include intended uses for training, hardware-in-the-loop, operator-in-the-loop, wargaming, tactics development and refinement.

Embracing a Culture of Collaboration and Reuse

In keeping with General Saltzman's LOE 3 "Partner to Win" the NSTTC-D Increment 1 development facilitates a need to identify opportunities to leverage existing capabilities and form alliances for mutual benefit. Because of the short Increment 1 timeline inventing new capabilities will be considered only as a last resort. An early collaboration was formed within the NSTTC-D with the US Air Force and most significantly with the Air Force Research Lab (AFRL). The NSTTC-D Program Office and associated technical teams have initiated engagements with other Department of Defense (DoD) Services and Agencies (e.g. Missile Defense Agency and Defense Intelligence Agency Intelligence Centers, industry, and academia [e.g. Georgia Tech, Utah State University Space Dynamics Laboratory]) to identify opportunities for reuse of simulations, models, tools, and data required to plan and execute a variety of simulation scenarios to demonstrate Increment 1 capabilities. As those scenarios are refined the need to identify still more opportunities for reuse and collaboration is certain. To be successful in the long term the NSTTC-D must work with the M&S community to develop a robust set of standards, interfaces, and developer's guides.

A BRIEF OVERVIEW OF THE NSTTC-D'S ENGINEERING PROCESS

The NSTTC-D uses an approach comprised of several, mutually beneficial engineering processes. The first process, mission engineering, utilizes a structured and purposeful approach to mission decomposition, providing detailed requirements sufficient to support a test or training mission. The second process, systems engineering, utilizes the requirements from the mission engineering process as well as many other requirements sources, and constructs digital models that support a test or training program's system requirements, design, analysis, verification, and validation. Using the data from the previous processes the software engineering process develops the capabilities necessary to support the test or training event, utilizing agile principles in their execution. These processes are iterative in nature and can be executed throughout the life of the program.

The following sections provide additional detail for each of these three processes.

MISSION ENGINEERING

Introduction to Test or Training Mission Engineering

The DoD's Mission Engineering Guidebook (MEG) defines mission engineering (ME) as "[t]he deliberate planning, analyzing, organizing, and integrating of current and emerging operational and system capabilities to achieve desired warfighting mission effects" (Office of the Under Secretary of Defense for Research and Engineering, November, 2020). When analyzing the definition, it is clear the intent of the ME process is for the development of capabilities or tactics to achieve the mission objectives. Contrast that with the Defense Acquisition University (DAU) definition of test and evaluation (T&E) as a "process by which a system or components are exercised, and results analyzed to provide performance-related information" and training "the level of learning required to adequately perform the responsibilities designated to the function and accomplish the mission assigned to the system". (DAU Glossary, 2023) It becomes apparent the current MEG does not share a focus with either T&E or training. To remedy this difference, the MEG process was adapted to suit the test and training needs of the NSTTC-D.

Test or Training Mission Engineering Methodology for the NSTTC-D

To best meet the needs of T&E or training, a slight change in focus was needed for the MEG. The key objectives and attributes of the NSTTC-D are to provide an environment that enables the customer to:

- Assist development, evaluate functional and performance adherence to specifications, assess readiness to proceed to operational testing (Developmental Test)
- Evaluate the effectiveness and suitability of a weapon system with respect to its mission requirements (Operational Test)
- Prepare warfighters via realistic representations of their weapon systems and environment (Training), as well as providing for a robust SoS evaluation as pertains to mission objectives (Tactics, Techniques, and Procedures development, Large Force Exercises)

Figure 1 shows the ME process from the MEG. This process was adapted by placing emphasis on the first four steps.

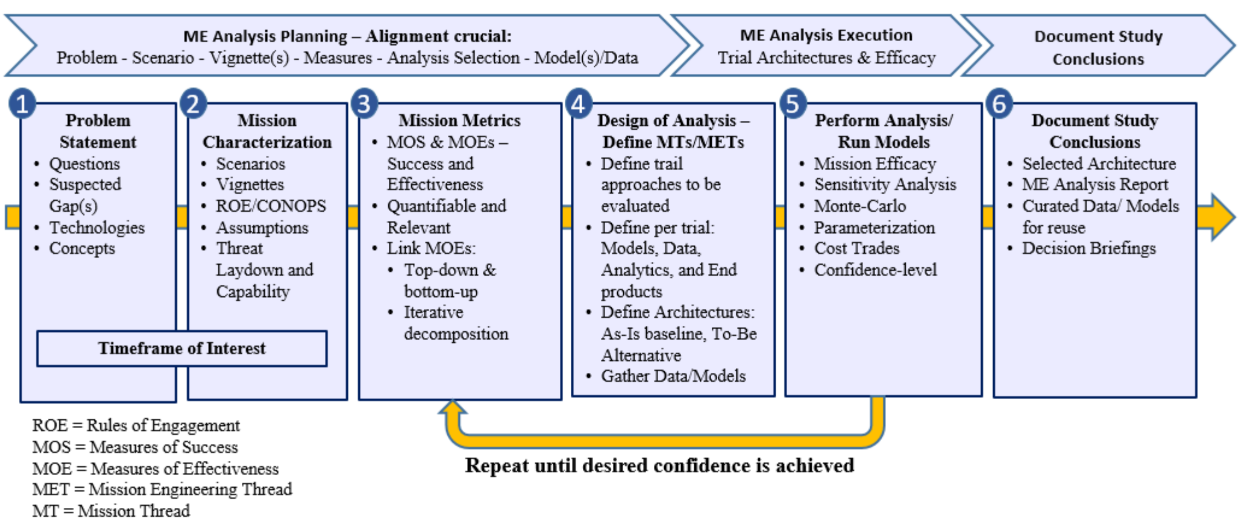

Figure 1. The Mission Engineering Process, per the MEG

To conduct test or training ME it is best to start early in a test or training program (e.g., before requirements are finalized.) The Problem Statement and Mission Characterization modules are accomplished primarily (but not exclusively) by the mission owner and the SPO and can easily be reused from their execution of the ME processes' final iteration. The Mission Metrics module is where the test and evaluation or training team become much more involved, providing definition to the requirements such that they support the content in the first two modules and adhere to requirement analysis and documentation best practices (see MIL-HDBK-520A). The Design of Analysis module primarily involves the test or training team's definition of mission threads, ME threads, and their detailed considerations given to the design of experiments necessary to produce technically adequate and statistically significant test results or meaningful conditions that achieve training objectives. The Perform Analysis and Document Study Conclusions modules do not apply to the tailored test and training version of this process, and as such are not explored further within this paper.

Connecting Test or Training Mission Engineering to the Larger Process

The primary purpose of a test and training range, like the NSTTC-D, is to provide the digital environment and data necessary to fulfill customer requirements. Oftentimes customer requirements are not as current or technically adequate as needed to test a system fully. As an example, typical test programs begin their requirements process years (sometimes a decade or more) before an actual test event is accomplished. The execution of the ME process is manually intensive, involving many working groups over many years. This process does not lend itself to easy or rapid adjustment to consider an evolving threat picture. Alternatively, many test programs within their sustainment phase just reuse the "tried and true" past test conditions without consideration for changed mission requirements. The same might be true for many training curriculums.

To better address these issues, the NSTTC-D team created the Test ME Profile using digital engineering (DE) tools (i.e. Cameo). The profile provides a means of conducting this process using the key artifacts and traceability within a digital data model. As shown in Figure 2 (adapted from OUSD of R&E, 2020) six modules were built with guidance text and examples throughout, all of which trace back to the NSTTC-D's adaptation of the ME process.

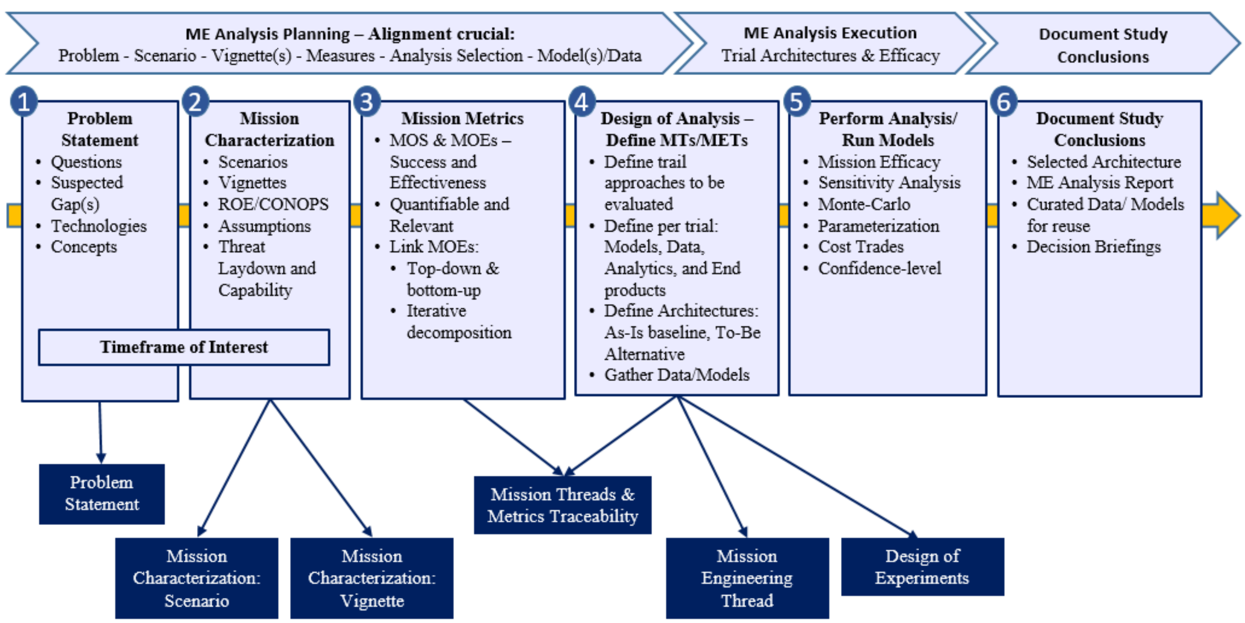

Figure 2. Test Mission Engineering Profile

This process ensures the requirements that comprise a test or training program (and delivered to the range) are technically adequate, statistically defensible, and consistent in their formatting and content. These requirements having been developed and documented using DE tools and best practices support additional DE products and efforts, such as: a model-based Test and Evaluation Master Plan; a digital Integrated Decision Support Key; and ingestion into the

NSTTC-D's system engineering model. Finally, having all this ME data within a digital model with full traceability from beginning to end makes it a much easier process to modify these requirements to address an evolving threat. This iterative and continual approach ensures that the NSTTC-D test or training environment remains relevant.

SYSTEMS ENGINEERING

Use of Model-Based Systems Engineering

The International Council on Systems Engineering (INCOSE) Systems Engineering Vision 2020 defines Model-Based Systems Engineering (MBSE) as "the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases. MBSE is part of a long-term trend toward model-centric approaches adopted by other engineering disciplines, including mechanical, electrical and software. MBSE is expected to replace the document-centric approach that has been practiced by systems engineers in the past and to influence the future practice of systems engineering by being fully integrated into the definition of systems engineering processes."

It is widely recognized that to fully describe a system several different views into the system need to be developed. A traditional documentation centric approach uses multiple documents to capture the various views into the system whereas a model-based approach moves the systems engineering team to a single source truth with multiple views to present. For these reasons the use of a model-based approach was pursued over a documentation centric approach to provide a common definition of required capabilities.

Goals of the NSTTC-D MBSE effort

The NSTTC-D team is developing the NSTTC-D system as a "first of a kind" space-based test complex, loosely based on the concepts used for terrestrial test ranges. Given uncertainty of a "first of a kind" system, the team recognized that it would not be able to accurately describe the total system from the start but would be discovering the needs of the NSTTC-D as it was being developed and ultimately used. To support this approach, the team adopted the Scaled Agile Framework (SAFe©) to integrate the needs of the stakeholders, architects, engineers, and developers.

To fully utilize SAFe© development, an approach was needed where the team could develop incremental descriptions of the system's behaviors that could be reviewed with the users and operators to gain their input and insight. The approach also requires feedback from the developers to influence future interactions of work. Figure 3 shows how this approach was adopted for the NSTTC-D.

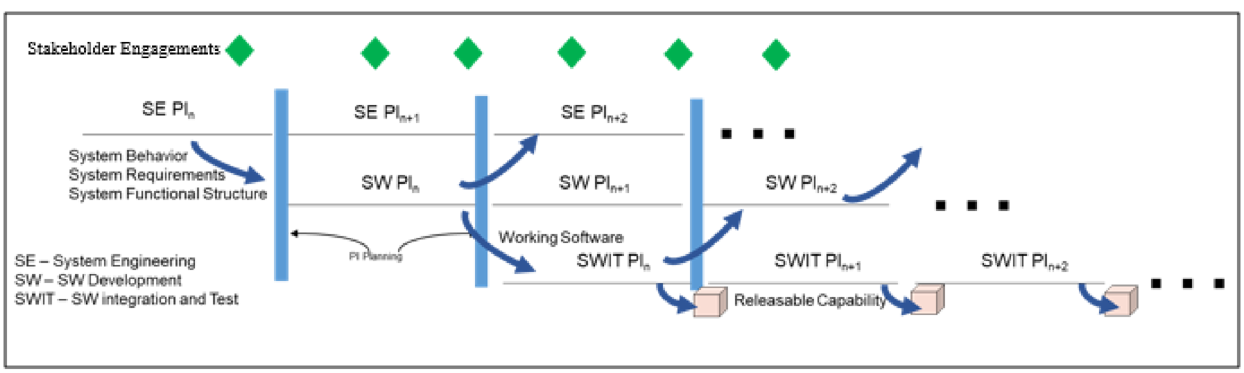

Figure 3. Integrated Systems Engineering and Development Approach

The Systems Engineering (SE) process defines future capabilities to be developed or integrated, at least one Program Increment (PI) in advance of development timelines. The team first focuses on developing the required operational behaviors and capabilities of the system. Once the operational behavior for an increment is developed, the team elaborates on those concepts enabling development. A working example of the operational behavior is then demonstrated with the users. User feedback is incorporated into the system specification and design. This approach enables the NSTTC-D team the ability to continuously incorporate the required features of the NSTTC-D.

MBSE Products

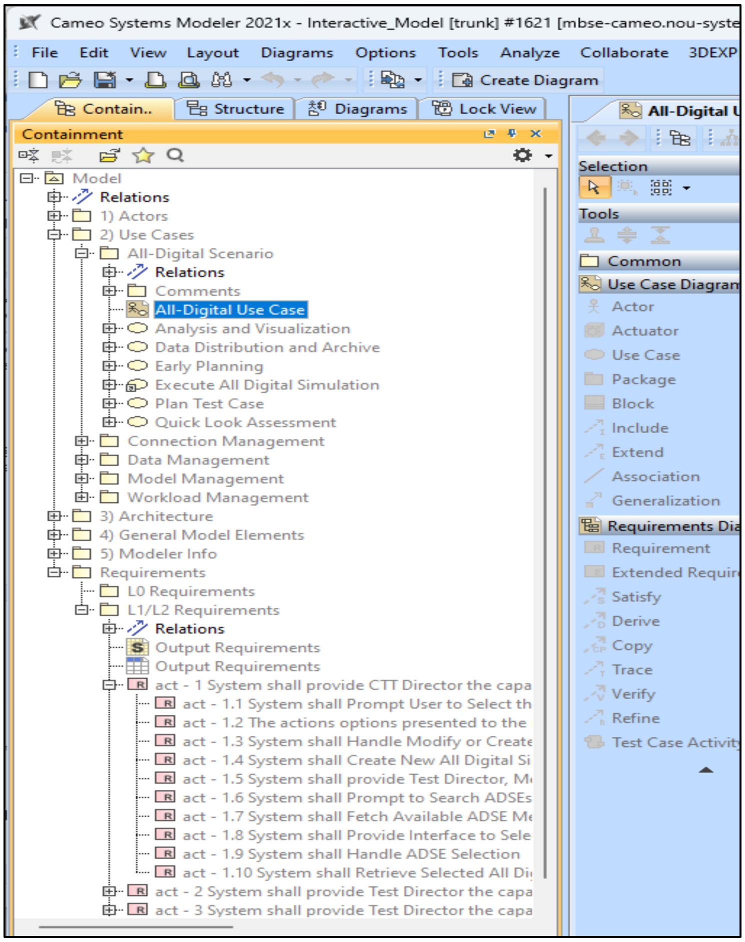

Figure 4: Containment Tree

The MBSE model developed for this program followed a simple approach of organizing the top-level of the containment tree along the lines of the major system viewpoints (Figure 4). Folders for the actor diagrams were included at the top level and are used to communicate what roles the users play while interacting with the system. The user roles were coordinated and aligned with the user's and operator's job descriptions. The next set of folders contains the use cases of the system. The All-Digital Scenario folder contains the set of use cases that pertain to the All-Digital scenario. This pattern is followed for the remaining categories of use cases. Level 0 (L0) requirements hold the requirements that provide the overall guidance for the NSTTC-D. The Level 1 (L1)/Level 2 (L2) Requirements folder contains the requirements that trace to the operational activities within the use cases (i.e., L1) and the decomposition of those into development level requirements (i.e., L2). The L1 and L2 requirements are derived from the L0 requirements and can be traced to those originating requirements.

Another significant set of viewpoint relationships in the model are those of the Requirements to the model elements. Within this view each of the system "shall" statements are shown, the model element to which it is traced, and the full description of the element that is contained in the associated documentation. This provides the developer a concise view into the requirements along with a roadmap to the full description and the context of the requirements provided by the elements within the model.

These sets of views provide a robust description of the operational and conceptual elements of the system. The developer elaborates on this model to develop the logical and physical (as-built) description of the system. The team is currently working to enhance the model by adding the additional functionality that will be developed in future PIs as well as representing the cybersecurity and other aspects of the system not driven by operational behaviors.

Issues and Benefits

The NSTTC-D overcame the challenge of limited MBSE, DE and SE (e.g., SysML) knowledge within the stakeholder organizations and a portion of the development team. Many of the stakeholders were not experienced with system specifications using a model-based approach and had issues understanding what was represented within the model.

Conducting in-model reviews where the team led these stakeholders through the model with detailed explanation and dialog facilitated better understanding and communication of the system requirements and development needs.

Another issue the team encountered early on was a lack of clear “shall” statements. This created uncertainty, misinterpretations, and questions within the software development team which was comprised mainly of prime contractors with a need to tie-in their products to measurable and contractual statements. Difficulties in navigating the model and understanding how the elements of the model represented the requirements of the system were mitigated with the addition of the L1/L2 Requirements module and associated relationships.

A significant benefit that a digital data model provides is an integrated description of the system. This minimizes the risk that individual system documents could be out of synch and/or contradict each other.

Similarly, the adoption of a digital engineering approach involved the users, operators and developers in the development of the model, which ensured all viewpoints were being addressed in a single, cohesive manner. This increased the probability that the “right” system is being built.

SOFTWARE ENGINEERING

Software engineering implements the capabilities defined through the mission engineering and systems engineering processes. The team leverages these inputs to develop the digital range software stack from the software factory. The term software factory is defined as “… a structured collection of related software assets. When a software factory is installed in a development environment, it helps architects and developers predictably and efficiently create high-quality instances of specific types of applications.” (Microsoft, 2014). The term, software factory, traces back to the late 60’s, early 70’s and more recently there has been a reoccurrence of the concept with the Department of Air Force Software Ecosystem’s software factories (i.e., Space Camp, Kobayashi Maru, and Kessel Run). The NSTTC-D software factory has similarities to the Air Force Software Ecosystem in that it uses similar tools but in general has a defined scope and focused objective.

The foundation the NSTTC-D software factory is constructed around People, Processes, and Tools. The requirements for the software factory come from the stakeholders (mostly the STARCOM Space Deltas) and the NSTTC-D engineering leads. These requirements are captured in system/ME artifacts that feed into the software factory. Ultimately, all these processes, tools, and people come together to produce the Digital Range software technology stack as shown in Figure 5.

One unique aspect of the NSTTC-D software factory is its joint nature; at the leadership level (Figure 5) there are both Space Force and Army leaders as well as Federally Funded Research and Development (FFRDC), University Affiliated Research Center (UARC), and System Engineering & Technical Assistance (SETA). Many of the leaders not only serve as an engineering advisory board, but also hold key roles at the software factory level. The contractors responsible for software development are also organized in a joint manner as there is one prime contractor for every three or four subordinate contracting companies. The joint nature of this software development requires a robust decision structure in place to remove blockers and keep work progressing to meet the short deadlines of Increment 1.

The governing body that provides the robust decision structure is the Joint Engineering Review Board (JERB) seen in the top of Figure 5. The main responsibility of the JERB is to provide epics (high level requirements, i.e., L0, L1, and L2) to feed the software factory’s agile framework[1]. The agile framework is the foundation of the processes within the NSTTC-D software factory.

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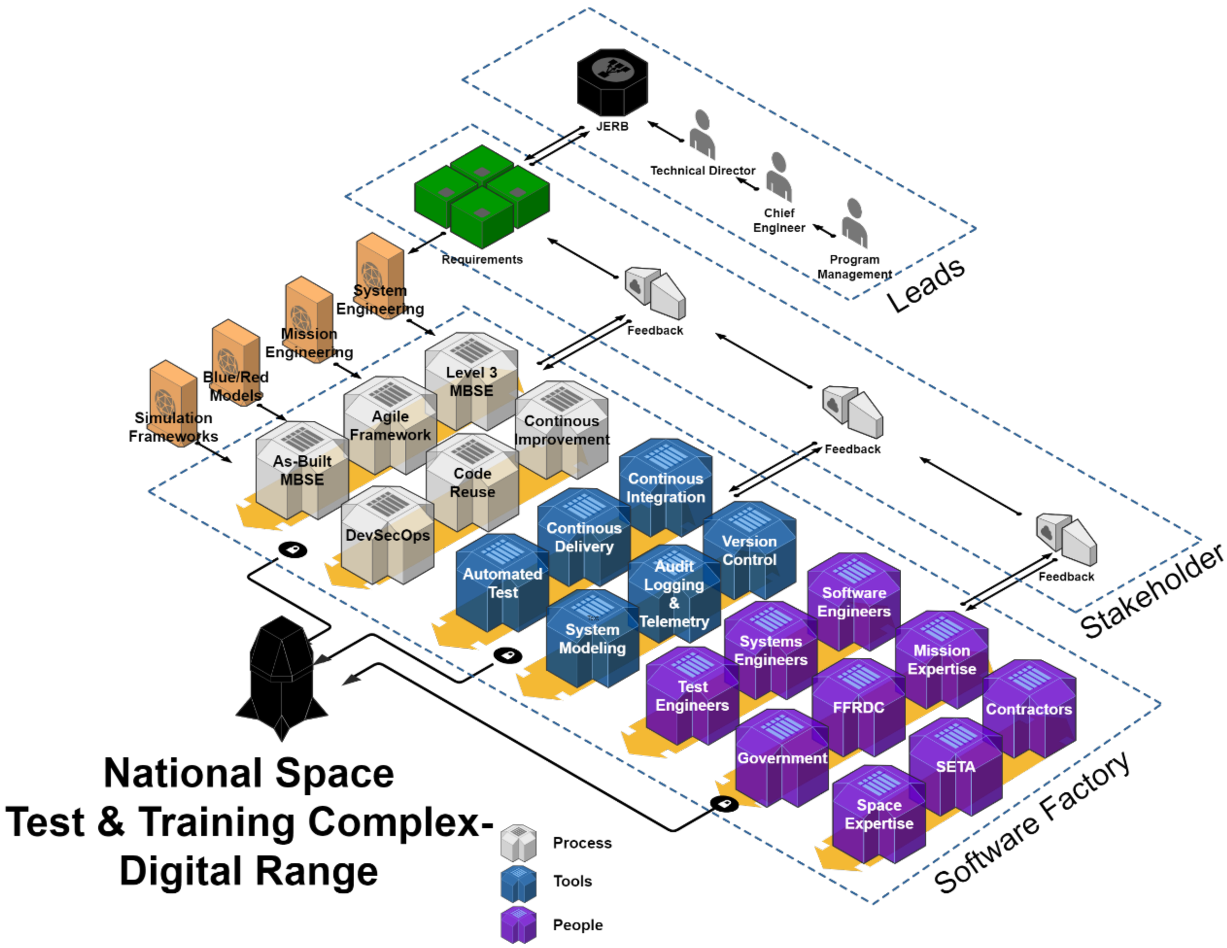

Figure 5: NSTTC-D Software Factory

Software Factory - Processes

The agile framework is structured into PIs. Each PI is 11 weeks starting with one week of planning and five two-week sprints. The agile framework consumes epics from the JERB and with the help of system & ME turns the epics into features, stories, and tasks. The agile framework breaks down the development into multiple teams lead by scrum masters.

In the case that the Conceptual (L1 & L2) MBSE models coming from system/ME the software factory system engineers have a process to build out the logical/physical layers (L3 requirements) as well as model the as-built software/system products.

One key enabler that allows the software factory to meet the Increment 1 schedule and performance goals is the reuse of software to include simulation frameworks, blue/red/gray models, and other enabling software stacks/libraries.

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[2] Scaled Agile Framework (SAFe©) is being used for Increment 1 but could be replaced with other agile frameworks in the future

Additional processes for assessing the software being integrated into the factory are in place. These processes mainly focused at the high-level to make sure the reused software will fit the Increment 1 needs. Additionally, there is an assessment needed to understand the resource requirements surrounding the reuse of a software component as opposed to independent development of equivalent software specific to the NSTTC-D's needs.

In parallel to the Agile Framework processes the software factory is continuously focused on improvement. This mainly involves examining processes, to include interactions outside of the factory boundaries. The need for efficiency in processes is key for the factory to execute the Increment 1 deliveries. Although not called out in Figure 5, culture is a foundational piece of all processes involving human interaction and continuous improvement is not just a process for collecting feedback and adjusting, but also a principle within the team culture that everyone holds themselves and each other to achieving.

The final process highlighted in Figure 5 is DevSecOps. This is typically associated with Continuous Integration and Continuous Delivery (CI/CD) automation tooling. There are several processes that must first be instantiated before tooling is selected for the CI/CD pipeline. In the NSTTC-D software factory the team started with processes, standards, and architecture to make sure the requirements for the production environments are met.

Software Factory – Tools

The tools being leveraged are chosen to assist in the efficiency and execution of software factory processes. Most notably this revolves around CI/CD, software versioning, and test. Modern commercial off the shelf software offerings provide a platform to do most if not all these things in one place. The tools selected allow for the storage and version control of the software as well as development task tracking and documentation wiki. The platform must also provide the automation features and ability to interface with other external software to complete the necessary steps of CI/CD and automated testing.

Because of the high visibility of the NSTTC-D program, the software factory must have robust logging which enables the development environment to be auditable and transparent to all stakeholders.

Software Factory – People

The NSTTC-D software factory has a unique combination of personnel supporting the program. On the government side the United States Army has civilian technical experts on M&S development and product owners on the development team. There is also a substantial FFRDC and UARC contribution providing ME and scenario development expertise as well as systems engineering, system architecture, and software technical guidance. Supporting the NSTTC-D leadership providing systems engineering and subject matter expertise on mission is the SETA support to the Integrated Program Office. And finally, the contracting teams that fill out the ranks of the agile development team. The contractors are comprised of a prime contractor and multiple subcontracted companies. The software factory acts as a single development team mixing expertise from both prime and subordinate companies. Some of the skillsets the teams have are test & software engineering, space experts, M&S, etc.

Ultimately, the software factory process, tools, and people come together to develop the NSTTC-D software. The software factory's initial implementation is meant to be very dynamic as the teams must be allowed to fail fast but recover faster and rapidly produce a one-of-a-kind capability.

SUMMARY

Defense of the US's military space capabilities is a significant contributor to combat effectiveness of the United States' defenses supporting all the Combatant Commands. Due to the uniqueness of the space environment, modeling and simulation will be essential to train Guardians, support acquisition decisions, and explore Tactics, Techniques, and Procedures for technologies not yet in existence. The USSF has taken the first step to set these capabilities in motion through the NSTTC-D. Developing a useful and enduring simulation for the NSTTC range requires a robust set of mission engineering, systems engineering, and software engineering processes. Beyond Increment 1 an acquisition strategy will be developed to leverage new competencies and technologies. Future developmental increments have not yet been precisely planned, but a technical roadmap is in the process of development. Capabilities under consideration include operator-in-the-loop, interoperability with other NSTTC/DoD ranges, hardware-in-the-loop, on-station training, large force distributed training environments, and advanced analysis (artificial intelligence/machine learning). While the NSTTC-D will evolve and grow toward satisfying the long term needs of the USSF mission, the techniques illustrated in this paper should persist well into future increments.

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