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The System Engineering and Test (TSET) Approach for Unprecedented Systems

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The rapid pace of development of new systems coupled with a strong desire from warfighters to quickly field systems with advanced technologies and innovation poses new Test and Evaluation (T&E) challenges. These challenges start with the realization that most T&E procedures are derived from a historical, requirements-based approach to acquisition, which inherently is a sequential process. For innovative and unprecedented systems, i.e., the kind of system for which there is no experience in building similar systems or in their test or use, T&E cannot follow a sequential approach. Throughout military history, development of unprecedented systems has occurred when there has been a simultaneous advance in technology and operational need such as is occurring now in the domain of unmanned systems. T&E needs to evolve to be integrated with the development process. Waiting for the results of developmental and operational testing will only exacerbate the delay in rapidly fielding advanced capabilities. This article presents the tenets of using the system engineering and test approach for evaluating unprecedented systems and moving testing to the forefront of the system development process.

Key words: Adaptability, collaborative development, CONOPS discovery, early involvement, emergent capabilities, evolving environments, experimentation, innovation, system alternatives, systems engineering and testing, unmanned autonomous systems.

The current Test and Evaluation (T&E) paradigm is founded in decades of experience, yet the world has changed significantly, particularly over the last decade. There is the realization that new test methods are needed to get our systems to the warfighter sooner; some strong sentiments have been recently expressed, which reflect the need for unconventional approaches to achieving this goal. U.S. Secretary of Defense Robert M. Gates, at his speech at the Air War College at Maxwell Air Force Base, Montgomery, Alabama, on April 21, 2008, stated:

> "For the kinds of challenges America faces and will face, the armed forces will need principled, creative, reform-minded leaders, men and women who…want to do something, not be somebody. An unconventional era of warfare requires unconventional thinkers." (Gates 2008)

Chris Dipetto, Deputy Director for the Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, stated in his presentation "A New Vector for Developmental Test and Evaluation (DT&E)" to the International Test and Evaluation Association, Tidewater Chapter, 2007 (DiPetto and Stuckey 2007) that we need to change "… the mindset of all persons involved to focus on trading greater capability for earlier fielding." And, the 2008 report of the Developmental T&E Committee of the National Defense Industrial Association (NDIA) stated that we need to "…specifically address T&E policy recommendations for incorporating T&E expertise early in the acquisition cycle, integrating developmental and operational testing, and improving suitability of weapon systems during development."

Numerous reports, findings, presentations, and committees are voicing a need for supporting a new direction in T&E, which often happens too late in a system's life cycle. This is especially true for unprecedented systems.

An unprecedented system is a system that has never been developed before. In a 1989 report from the Air Force Studies Board, an unprecedented system was defined as one for which development is based on a new technology, a new architecture, and/or a new acquirer/development team (i.e., they have never built anything like this before, or they have never worked together as a team), as opposed to systems with precedence, which include those for which the requirements are "consistent and well understood" (Beam 1989). This report detailed development methodologies that could be best used to reduce risk associated with the attributes of unprecedented systems.

It is interesting that at various times in military history, there has been a rapid advance in technology simultaneous with doctrine that has led to unprecedented new capabilities. These capabilities have often resulted from discovery-based experiments in exercises. One historical description of this comes from a fascinating article published in 1999 (Perry 1999). Perry reviewed the rapid development of air doctrine during the 1930s and the simultaneous advances in technology. The development centers of that day were co-existent with training and test facilities, which in turn led to simultaneous consideration of system definition, system test, and system use. It is in this spirit that we pursue a new approach—one that applies historical lessons—called The System Engineering and Test (TSET). TSET is enabled by approaches such as the Joint Mission Environment Test Capability (Lockhart and Ferguson 2008) and is coupled with evolving tools to support systems engineering to bring test considerations forward in the system engineering process. TSET also helps to consistently and effectively address test issues throughout all phases of the system life cycle. Further, the approach discussed will enhance the likelihood that different stakeholder constituencies (e.g., user, developer, acquirer, tester, trainer, sustainer) will be more likely to have a shared understanding of key issues related to the system during the different life cycle phases (Saunders 2005). This work is timely as current federal legislation is addressing the issue of earlier use of system engineering methods and test consideration in major weapons systems acquisition programs (U.S. Senate 2009)—points that are consistent with a recent National Research Council study (Kaminsky and Lyles 2008).

This article presents the tenets of using TSET for evaluating unprecedented systems and moving testing to the forefront of the development process. The overarching approach emphasizes three major aspects; specifically, there is a strong need for

- earlier discovery and experimental testing of systems and engaging the evaluators in the T&E process sooner rather than later;
- testing across a larger breadth of representative and realistic operational environments, both live and virtual, while stressing evaluation of unprecedented, innovative, and interacting systems operating in unpredictable environments; and
- engaging in campaigns of experiments to explore system alternatives through the co-evolution of systems, technologies, and concepts of operations (CONOPS).

The challenges

When systems are tested, there is usually one or a few variations of the system operating in the test environment, yet today's warfighting operations require collections of disparate platforms developed by different contractors to be interoperable, support joint and coalition missions, and be effective in environments that are unknown or were unforeseen when the contract specification was written. The U.S. Air Force Science Advisory Board recently noted "… it has become increasingly apparent that although the United States Air Force (UASF) *buys* systems in isolation, it does not *use* systems in isolation" (Saunders 2005).

Today's testing has a strong focus on system requirements and in assessing whether each requirement is met. New T&E methods are needed to allow system capabilities to be discovered and evaluated without the strict confines of a pass/fail test and to enable an understanding of the system relative to potential and actual missions. Based on the mission or operational environment, unprecedented systems and systems-of-systems may execute behaviors that cannot be precisely predicted. Discovery of capabilities and assessments of systems need to support evaluation of actions and judge whether the actions are reasonable and acceptable. Testing of these systems needs to focus on capabilities and potential missions. These notions are straining the current methods of T&E. New approaches to T&E must be adopted to support system discovery, innovation, and advances, where the T&E methods evolve and adapt, just as the systems do.

The challenges that seem to plague many programs include

- an incomplete understanding of the operational need, the potential operational need, and the related performance requirements;
- an often inadequate and ineffective tradeoff analysis between performance, schedule, and cost requirements, where performance is broader than component performance;
- an inadequate approach for defining key performance parameters (KPPs) that links them back to

needs, requirements, and potential needs and capabilities;

- testing considerations, both operational and developmental, that start too late;
- the lack of a shared understanding by stakeholder groups, including the developers, the testers, and the end users; and
- acknowledging that while the Department of Defense (DoD) has many facilities to support T&E, these resources are mostly devoted to formal systems testing (i.e., there is an inadequate ability to *simultaneously* address technical, operational, and production gaps in capabilities).

Many of today's systems are evolving to be much more capable of supporting collaborative and unscripted operations. Systems are moving away from being point solutions to instead being used in unorthodox ways. Based on the mission or operational environment, these systems have the potential to be used in ways that were never precisely predicted. Advances in sensors and systems are supporting operations in unstructured and hostile conditions, while providing the opportunity to identify new capabilities in situ. Systems are operating with other systems that have differing capabilities. Their operations are becoming more and more characterized by nonlinear responses and responses based on incomplete information. Yet, these characteristics do not preclude robust operations. What is unique is that new approaches are needed for discovering the capabilities and then testing and measuring this robustness, especially in nondeterministic and evolving environments. In today's wartime environment, where we need a rapid turnaround to get systems to the warfighter, adaptability is crucial.

Unprecedented systems will be used to their fullest extent only when the end user is confident in their operation. The best way to accomplish this is to increase the interactions between developers, testers, and users. Early involvement with operational test agencies will result in early identification of operation T&E expectations and needs. T&E needs to provide methods to explore system alternatives through innovative interactions of technologies, CONOPS, and experimentation and to explore the interplay between technology and CONOPS, just as was done in the 1930s.

The big "E" word

It has been said many times that T&E activities do not fund Experimentation, the *other big* "E" word. Somehow, the view that experimentation must be kept separate from T&E has infiltrated our systems thinking at a time when T&E and Experimentation truly need to be integrated. This does not mean that T&E must fund Experimentation or that program managers must pay for extra T&E out of their program development budget. It means the two must be coordinated and work together. It includes concepts as simple as providing technology developers with validated T&E tools to use when they are doing their own testing, and it includes concepts as expansive as the double helix, system-level experimentation approach described in the Air Force's 2006 Scientific Advisory Board report (Cross and Fouse 2006). The double helix approach supports discovery-level experiments by the testers as well as the developers *(Figure 1)*.

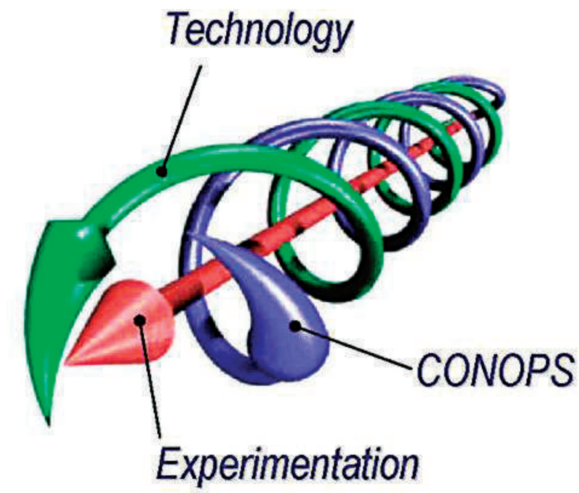

Figure 1. Co-evolution of systems. The double helix. Adapted from Air Forces 2006 Scientific Advisory Board report (Cross and Fouse 2006).

For unprecedented systems, where discovery experiments are needed to explore new CONOPS and new means to satisfy the CONOPS, co-evolution is required. Co-evolution is the idea that innovative technologies and CONOPS evolve and are developed together and evaluated through experimentation. This is key to creating a shared understanding of how the systems work, how they will be used, and how they could be used. T&E needs to be part of the experimentation process, and experimentation needs to be part of the T&E process, because a significant amount of testing, albeit system development testing, occurs early in the development process and is effected through experimentation.

The Air Force Scientific Advisory Board (Cross and Fouse 2006) noted that system level experimentation "increases the ability to discover game-changing ways to 'fly and fight' BEFORE the fight." Experimentally derived systems development has proven that higher payoffs are attained over requirements-focused devel-

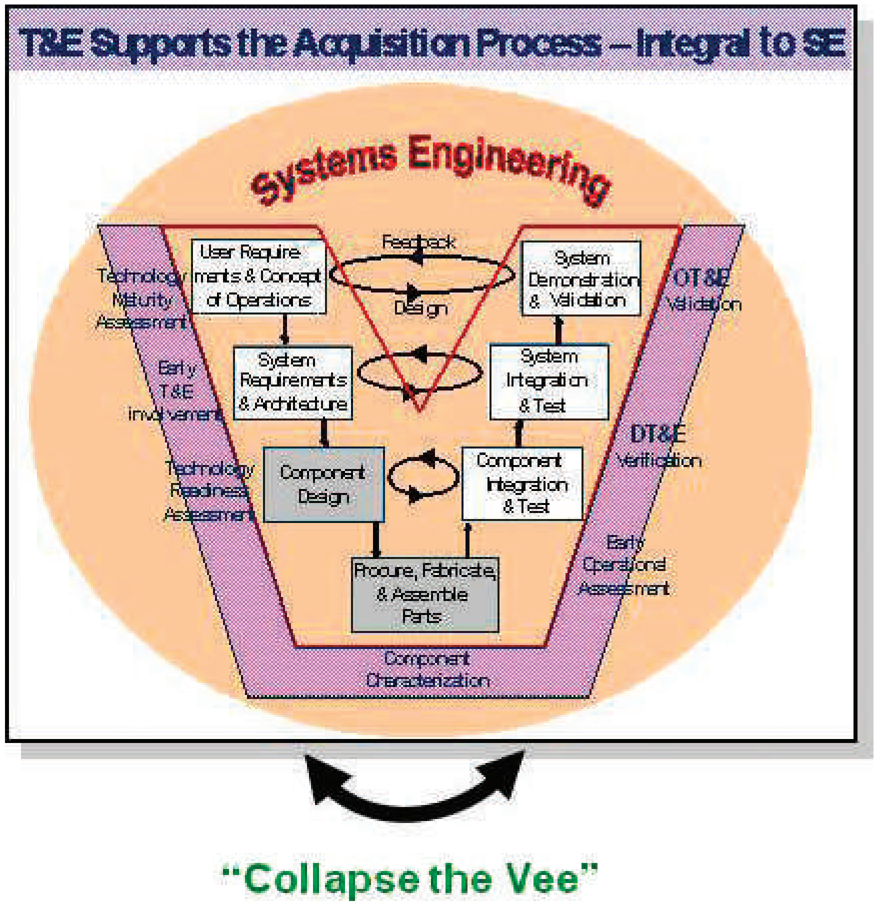

Figure 2. Collapsing the ''Vee'' so that testing and evaluation becomes an integral part of the Systems Engineering (SE) process.

opment. The Predator unmanned air vehicle was declared "not operationally effective or suitable" (Pogo 2002), yet it was deemed an immediate success since it could transmit live video feeds (Newman 2002). The Predator went from concept to deployment in less than 30 months. If experimental testing had been included before production, many initial glitches and cost increases may have been averted, and the Predator may have passed operational evaluation (Pogo 2002). The Predator evolved from an Advanced Concept Technology Demonstration (ACTD), and although the Predator is in high demand, even ACTD experimentation is not enough. Experimentation may be conducted through ACTDs or Joint Capability Technology Demonstrations (JCTDs). However, these programs are largely demonstration experiments, not the discovery experiments that are needed to explore and understand development of unprecedented systems.

One of the main tenets of system-level experimentation is to conduct iterative campaigns of discovery experiments to create a deeper understanding of future environments. Experimentation must be with the system, not just the technology, and it must stress the system via unconstrained adversaries. Is this experimentation the responsibility of T&E or is it a program manager's responsibility? The answer is "yes" and "yes"; everyone must be involved. Yes, it is experimentation, but tools to assess the system should come from T&E; the stakeholders (end users, warfighters, developers, and testers) must partake in early discovery experimentation. The result will be a better warfighting capability.

Collapsing the "Vee"

The best way to begin addressing these challenges is to develop new test technologies and approaches that increase interactions between developers, testers, and users. This amounts to collapsing the "Vee," so that T&E becomes an integral part of the system engineering process *(Figure 2)* (Buede et al. 2005). Constant, interactive feedback from the testers to the developers is crucial. To save both time and money, as test methods are developed and validated, they need to be promulgated among program managers for use in their programs. Newly developed test methods pro-

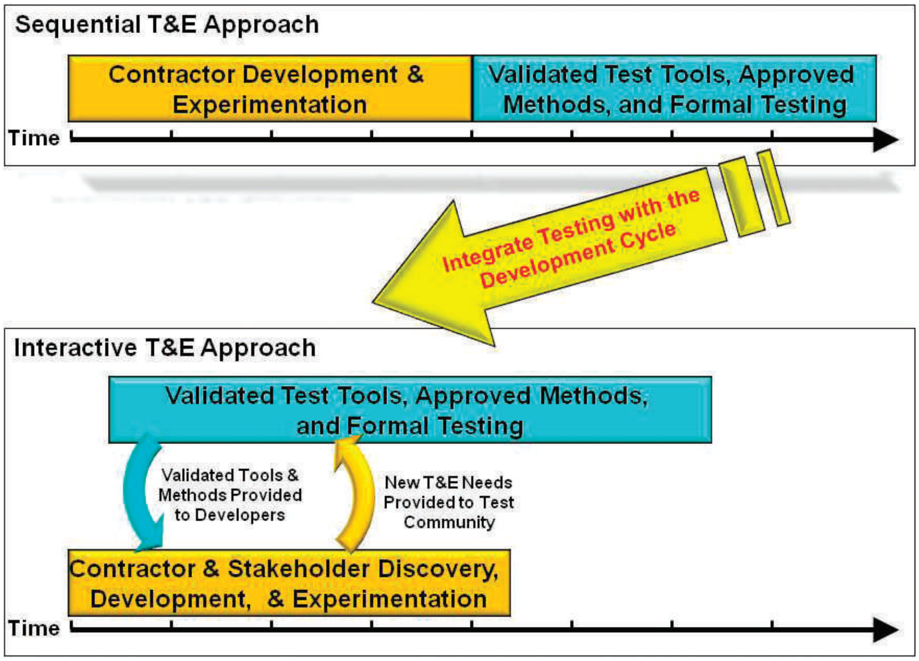

Figure 3. Integrating testing and evaluation into the development cycle.

vided to developers will allow system capabilities to be evaluated and enable an early understanding of the systems relative to mission success. As discovery, experimentation, development, and testing become aligned, the turnaround time to get systems to the warfighters will be dramatically reduced, resulting in T&E becoming part of a quick reaction capability to get systems in operation.

New approaches to T&E can be adopted that support advances in system capabilities, where the T&E methods evolve and adapt, just as the systems do. *Figure 3* shows how the T&E process can be adapted to support developers by providing them validated tools for experimentation, while the developers provide feedback to the T&E community on identifying new test needs. The relationship between testers and developers becomes interactive and integrated, where testers working closely with developers will discover new system CONOPS, and where developers attain an understanding of test needs. This relationship is integral and will accelerate introduction of innovative systems.

The TSET concept

The TSET concept is based on the double helix, system-level experimentation concept. The concept emphasizes that exercise-based experiments are needed to explore new CONOPS and that they are also needed to satisfy the CONOPS. Co-evolution is expected and is key to capturing these capabilities as part of the program record and to help create a shared understanding. By using the same environment for both developing the system performance requirements and testing the system, one can replay any state of the system so that a shared understanding is facilitated. Methods to support dynamic representations of test plans are linked to the experimental test environment, which then generate discussions on how KPPs will be measured and how the requirements will be tested. A collection of T&E tools can be used to facilitate these interactions, so that experimentation is not biased based on a contractor's suite of tools.

Validated and exploratory modeling and simulation tools can enable analysis of emergent systems in environments that are difficult to physically replicate or that present unforeseen circumstances. They allow numerous scenarios to unfold in shorter amounts of time, and they support new approaches to introspection assessments of the systems. T&E tools to support the experimental environment can assist in testing physical aspects of the systems at all levels, from component testing to bench testing and ground testing through collaborative operations. They can support testing payloads, sensors, weapon management, and data collection for large amounts of disparate test data. These would be the same tools that are used for actual T&E measurements, but they are provided to the experimental sites to support early testing and assessments. They also enable communication of shared visions and expectations, as well as the development of new CONOPS and the discovery of new uses for the systems. Tools for identifying new capabilities or analyzing new CONOPS are also needed to enable increased operator interactions with new families of systems, to provide metrics for mission effectiveness, to assess new types of "-ilities," and to determine new approaches for discovery and evaluation of unprecedented systems. These tools cannot be provided after the system is completed but rather need to be developed in concert with the technologies, the system, and the CONOPS. Everyone must be engaged from the start.

As complexity and capabilities increase, additional test scenarios will be needed to analyze and assess the operational envelope of unprecedented systems. As the number of tests increases, the testing time will also increase, and a larger burden will be placed on T&E. New testing approaches are needed that relieve this burden while ensuring the operational envelope is covered. System developers and testers need to interact early on in the development cycle to explore the test needs for these systems and to identify how to best test capabilities.

While it is difficult to reduce the level of complexity, system transparency can be increased. By employing experimental testing through TSET, transparency can be increased, and the states of subcomponents in the system can be exposed to allow evaluators to inspect the intent of these subsystems and discover new uses for the systems.

TSET applied to unmanned systems

As an example TSET domain of application, consider unmanned systems. Today, unmanned systems are operating in-theater with untested collaborative capabilities. The vehicles are heterogeneous, in that they are developed by different contractors they have different levels of autonomy, they have different sensors and capabilities, and they are physically disparate. Unmanned air vehicles built by one contractor have never autonomously collaborated with unmanned surface vehicles built by another contractor, and no one knows how they would perform if deployed together. Their integrated use, however, is rapidly growing in the military. As improvements in autonomy, sensing, and reasoning advance; collaborating, multi-vendor unmanned systems will be increasingly employed to support challenging, tactical operations. The anticipated increase in sophistication drives the need to collaboratively design, develop, test, and evaluate heterogeneous unmanned vehicles for full-spectrum dominance and joint operations (Robinson, 2008). We need a paradigm shift in T&E of unmanned systems that enables rapid discovery and flexible assessment of force-on-force capabilities of the effectiveness of disparate unmanned systems collaborating in theater-wide scenarios, while simultaneously ensuring safety of operations and stability to programs of record.

Addressing the test complexity of interacting, heterogeneous, intelligent, and autonomous unmanned systems requires a flexible experimental test environment for coupled hardware and software capability discovery and validated assessment tools for quantifiable analysis. TSET operations in experimental test environments support a less-formal, but physically meaningful way for unmanned systems developers to bring their systems for early-on exploration and testing, and make it possible for the end users and testers to become involved in the product sooner rather than later.

To enable this objective, TSET has several components: test tools and methodologies for component evaluation, modeling and simulation for high-level discovery, CONOPS exploration, analysis, and a flexible experimental test environment for coupled hardware and software experiments. These components are linked by analysis tools for assessments prior to fielding the systems and for quantifiable on-range evaluations of the systems. *Figure 4* presents the concept.

The modeling and simulation enables discovery and evaluation of potential emergent capabilities in environments that are difficult to physically replicate or that present unforeseen circumstances. It provides methods and tools to assess the impact of collaborative unmanned vehicle decision making, and it helps capture the amount of human awareness needed by the testers of the systems. As unmanned systems become more autonomous, the capability to communicate knowledge and information to the testers may not exist. For example, as systems become more autonomous and physically smaller (e.g., micro-unmanned vehicles), less data may be transmitted to a tester (because of power and size constraints) while, simultaneously, the systems will be making decisions autonomously and in unpredictable environments. It is not clear what information is necessary for the tester to be able to evaluate the autonomous aspects of these systems. Test tools need to evolve in parallel with the systems to determine what is really needed to test these systems and to discover what the systems are inherently capable of doing. The testers can stress the systems in unforeseen situations within a controlled digital environment with tools that are flexible and adaptable. They gain an understanding of the systems and their capabilities, which allows them to explore new CONOPS.

Such tools do not currently exist, and since technologies are still in development, it is difficult to create specifications and requirements for the *assessment* tools (let alone the systems). However, baseline test capabilities can be initiated and adapted as the systems evolve.

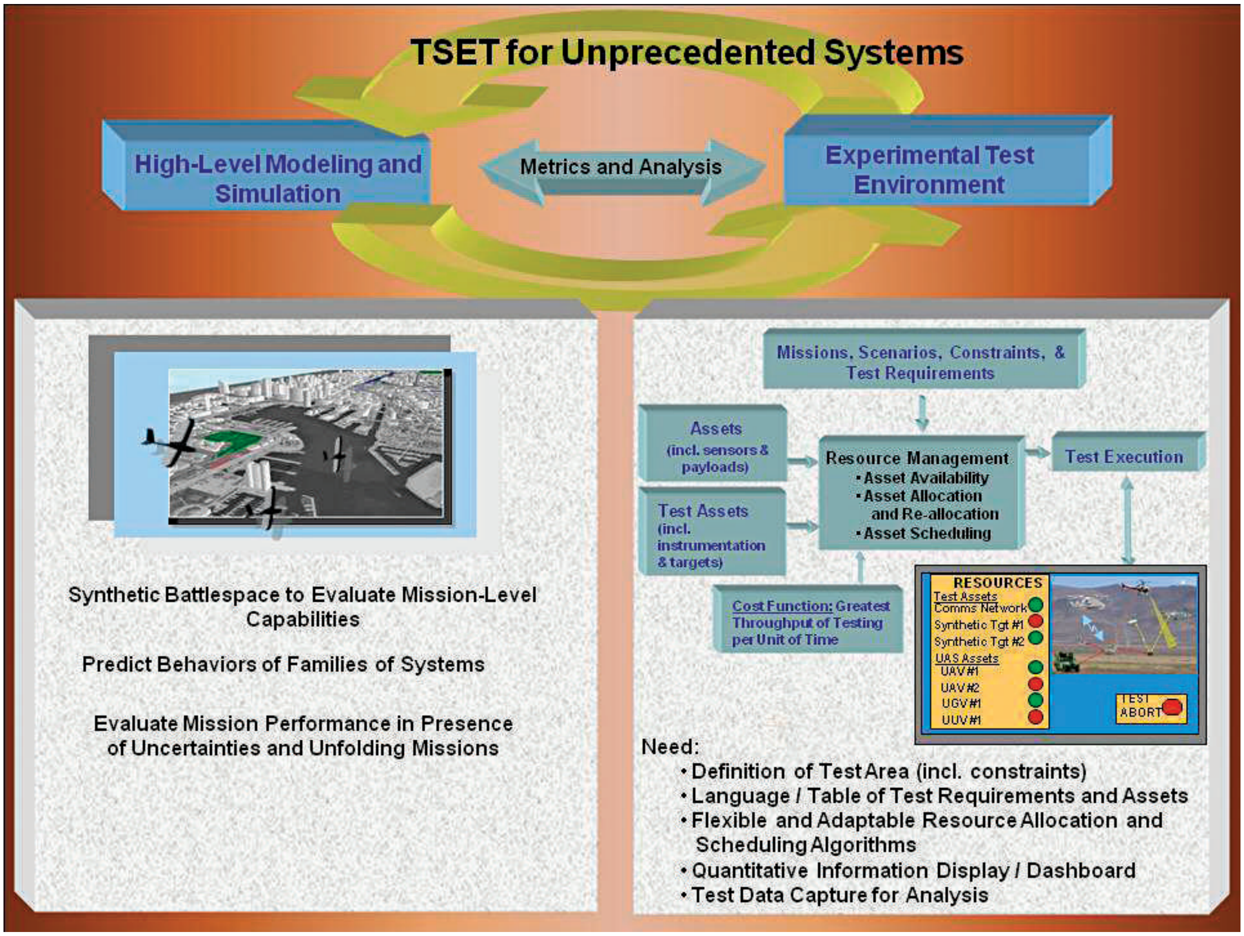

Figure 4. The System Engineering and Test (TSET) for unmanned systems.

For example, an unmanned system may display behaviors that emerge from actions and interactions with other manned and unmanned systems. The behaviors may be nondeterministic and unpredictable. System engineers may observe an emergent behavior and integrate technologies to reinforce or suppress what is observed, but it is difficult to know the performance gains attained from the emergent behaviors. Unmanned systems T&E requires capabilities to predict how modifications in the external environment may alter a behavior or possibly trigger an emergent behavior and what effect it has on mission performance. Tools are needed for exploration and assessment of unmanned systems that leverage advances in knowledge discovery and predictive analysis and that support an ability to identify potential outcomes of unmanned systems operations in nondeterministic environments. TSET methods allow unmanned systems capabilities to be discovered and evaluated without the strict confines of a requirements test and, instead, enable an understanding of unmanned vehicle autonomy relative to mission success.

The experimental test environment supports a less-formal, but physically realistic area for unmanned systems concepts to be tested early. It enables aspects of systems to be discovered and evaluated while there is still time to make adjustments. It enables end users and testers to become involved with the product sooner rather than later, and it enables exploration of physical interactions among multi-vehicle missions, where systems may have common goals, but decentralized control.

The modeling and simulation and the experimental test environment are connected by analysis tools. As the shift from systems-based development to capabilities-based development continues, new metrics and methods are needed to assess systems. The emphasis on system measures of performance will shift to measures of effectiveness, and those measures of effectiveness will evolve based on the systems, scenarios, and missions that are identified by testers and developers alike during early experimentation. For example, testing long-duration, persistent unmanned system operations will require long-duration analyses. New metrics will be needed for testing a different type of information overload in these long-duration scenarios, but we will not know what information is needed until we begin system-level experimentation.

Conclusions

As more unprecedented systems are used for multimission or collaborative operations, new challenges are placed on testing. There is a strong need to conduct systems engineering testing for coupled exploration of technologies, CONOPS, and capabilities. This is driven by increased connectivity, increased capabilities, and operations in complex adaptive environments. The TSET concept enables testing unprecedented systems and operations, where new information and knowledge are gained, and where increased interaction and integration results from early involvement from the end user. The TSET approach allows T&E to evolve as the systems evolve. It enables earlier testing of systems and engages the evaluators in the T&E process sooner. It supports testing across a larger breadth of representative and realistic operational environments, and it can be attained without causing major disruptions to current programs, but recognizing changes are needed. ❑

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