Systems Engineering and T&E: 'Till Death Do They Part

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Once a hot topic, systems engineering has received very little attention over the past decade, leading some to conclude that the passing systems engineering fad no longer holds much relevance. Or, perhaps experts have so completely mastered this discipline in the last 30 years, that it is now an integral part of system development, operating in the back plane of big programs and needing little attention. Neither scenario is true, and both are dangerous paradigms. In fact, signs now indicate that systems engineering actually is experiencing a renaissance. Adherence to its principles is again a prerequisite to successfully fielding today's complex systems, just as it was in the 1960s. The difference now, however, is systems engineering's absolute dependence on rigorous test and evaluation. This paper explores that partnership, focusing on the three primary challenges—requirements evolution, program-wide commitment and skill mastery—that these two disciplines face in modern acquisition programs.

In the 1960s, experts institutionalized systems engineering to fill the need for an organized, disciplined approach to developing increasingly complex systems. Systems engineering principles have proved themselves over time. Programs that have adhered to those principles have yielded some incredible products, and those that have not have paid a price, either through outright failure or through falling substantially short of desired performance.

Some experts have defined systems engineering as the effective application of scientific and engineering efforts to transform an operational need into a defined system configuration. And, this is accomplished through top-down iterative process requirements definition, functional analysis, synthesis, optimization, design, test and evaluation (T&E). An opposing approach calls for developing a system from the bottom up without a well-recognized, higher order structure. In such programs, integration usually occurs through the application of "brute-force" methods, using a trial-and-error approach (Blanchard 1991).

In each development program, systems engineering's biggest challenge historically has been found at the edge of the technological advance's frontier, and many great challenges have been met at each system level. Over the last 25 years, the frontier in Navy ship acquisition has moved from the combat system integration level in the 1970s to the total ship level in the 1980s. Currently, in the 1990s, that unexplored territory can be found at the battle group interoperability level.

T&E also finds its greatest challenges at the battle group interoperability level, for it is there that limitations in proven measurement and analysis techniques, as well as the elusiveness of "ground truth," can undermine its effectiveness. Not only do systems engineering and T&E have the same frontier, they also have come to depend on one another for success. No authoritative text on systems engineering exists in which T&E is not described as integral to its processes. This author has coined the term "T&E engineering," which refers to applying systems engineering principles within T&E planning and execution. In a previously published work, this author also noted that, "Today, successful systems engineering in a development program involves much more than the aggregate of engineering of the individual subsystems

plus a phase of integration of the subsystems. So too, T&E engineering at the overall program level must be more than an aggregation of subsystem T&E engineering." (Reynolds 1997)

The critical and interdependent natures of systems engineering and T&E now are more pronounced. One reason for this new prominence is that the definition of what constitutes a system has been expanded dramatically. In Navy ship design, for example, what were considered relatively stand-alone sensor and weapons "systems" 25 years ago were incorporated into *combat* systems in the 1970s. The process began as a relatively loose integration at first and then was tightened. In the 1970s, construction of the two USS *California* (CGN 36)-class nuclear powered cruisers included installation of the first forward-fit digital fire control system for the surface-to-air missile system. However, its antisubmarine warfare fire control system was analog.

Four USS *Virginia* (CGN-38)-class cruisers were built immediately afterward. The *Virginia*-class was outfitted with a digital antisubmarine warfare fire control system, as well as closer systems integration to achieve quicker reaction times. One full decade—and several ship classes and much technology advancement later—the USS *Ticonderoga* (CG-47)-class cruisers began entering the Navy's fleet. At this juncture, the combat system was truly integrated, and the individual sensor, fire control, weapons and other components became its subsystems.

The USS *Arleigh Burke* (DDG-51)-class destroyers joined the Navy fleet in the early 1990s. These new destroyers took design to the next step. Optimized at the total ship level, this class had the best surface ship design to date. Even ship and crew survivability were designed-in at the total ship level to the point where the ship could "fight hurt" much better than any previous class of surface combatant. Emphasis on this capability was heightened both in response to "live-fire T&E" legislation introduced in the late 1980s, and as a result of much work done by the Office of the Secretary of Defense and the Navy as well.

With the Navy's newest engineering focus on integration at the battle group level, new systems now enable ships in a battle group to communicate more efficiently. They also are capable of detecting and engaging targets in a coordinated manner, thus greatly increasing their ability to perform their missions and to protect themselves (*Figure 1*).

Not only do the new integration and interoperability levels serve as drivers in new ship designs, but they are being back-fit into existing ships as well. However, it is difficult to perform systems engineering and T&E for such back-fits, particularly because substantial changes occur over a relatively short time. When the Aegis weapon system, for example, became operational in the early 1980s, it had five million lines of computer code—more than the Space Shuttle or the B-2 bomber. Upgrades since have greatly increased the system's computing power. The current Baseline 6 upgrade alone adds 15 million lines of code (Meyer and Geary 1998).

Figure 1. Interoperability among Navy battle group ships is the frontier in SE/TE today

The systems themselves were complex, and the functions considered an inherent part of those systems continued to expand. In the 1970s, systems engineering focused on interfacing and integrating hardware and computer software. As system complexity increased, supportability and operator training needed to be "engineered in" at the outset to ensure optimal system performance. Later, man-machine interfaces and man-in-the-loop were more formally considered. In many current systems, tactics, information handling, and even politics, must be considered as part of the systems engineering process. Underscoring the significant new emphasis on battle group interoperability, Admiral Jay Johnson, USN, Chief of Naval Operations, has called it "a fundamental shift from what we call platform-centric warfare to something we call network-centric warfare." (Johnson 1998)

The same basic *principles* of systems engineering have enabled the Navy to advance so quickly from total subsystem, to total combat system, to total ship, and

now, to total battle group integration. The *principles* of systems engineering remain the same and are as applicable today as they were decades ago. What differs now is the *level* of systems integration to which the principles must be applied.

Experience shows that today's complex systems face three major challenges in successful development, and they are the same for both systems engineering and T&E. These challenges include difficulty defining the requirements; forging a total program-wide commitment to the requirements; and applying the proper experience and tools. To underscore the inextricable partnership between the disciplines of systems engineering and T&E, hereafter they will be referred to as SE/TE.

Evolving the requirements

"Beginning with the end in mind," according to Stephen Covey, is one of the seven habits of highly effective people and organizations (Covey 1989). In the acquisition business, the end in mind is a new mission or capability. A system's successful performance in full-scale developmental and operational T&E is proof that the end in mind has been achieved. Program requirements are of paramount importance to SE/TE. This is demonstrated by the fact that more than 50 percent of mission-related deficiencies uncovered during full-scale T&E are traceable to ambiguously written requirements. Such ambiguity often is borne of requirements that come too early or too late, or that are too numerous, too few, too high or too low. When those problems occur, good SE/TE is undermined. In fact, it never has a chance.

An example of what could have been too many requirements at a program's top level is a Navy experiment launched several years ago. This initiative, known as Smart Ship, sought to evaluate whether or not ship crew size could be reduced, primarily through automating tasks and functions that previously required significant human intervention. The experiment was tremendously successful, and leaders agreed to implement a program to buy and install new systems and equipment on several ship classes to observe these results.

But, when participants applied the old acquisition process paradigm, some called for a significant specification of quantitative thresholds and pass/fail thresholds for the sake of "good T&E." They wanted top-level Smart Ship program documents to specify requirements for such issues as number of crew members, their rank and rating, and from what ship departments they would be taken, as well as what new systems/equipment characteristics would be considered pass/fail T&E criteria for the program. What these proposals stated, in effect, was that good T&E required that the noble, simple objective of reducing crew size could not be held as the single, paramount, overriding objective, with the other parameters being dependent variables.

The acquisition process itself has a direct impact on the bureaucracy's sometimes apparent tendency to conspire against a proper hierarchy of requirements evolving in a systematic, timely manner. Michael O'Neill of the Georgia Tech Research Institute observed that the U.S. Defense Department's regulations prescribe a sequential development process with established periodic milestones supported by major program progress reviews. This has been referred to as the "relay approach," wherein the entire program is forced to proceed at the pace of its slowest element (*Figure 2*).

As a natural consequence of this situation, some have come to view the test and evaluation community as emphasizing its gatekeeping responsibilities at the expense of its duty as creator of knowledge. Exceptions to the relay approach have been necessary in the case of command and decision systems, wherein an evolutionary, piecemeal approach to SE/TE, known as the "Sashimi" approach, has been accepted. But it appears that the U.S. Defense Department increasingly is moving toward the more holistic "rugby" process—an industry staple since the mid-1980s—in which a team tries to go the distance as a unit, passing the ball back and forth, to foster a fast, flexible process for new product development. (O'Neill 1997).

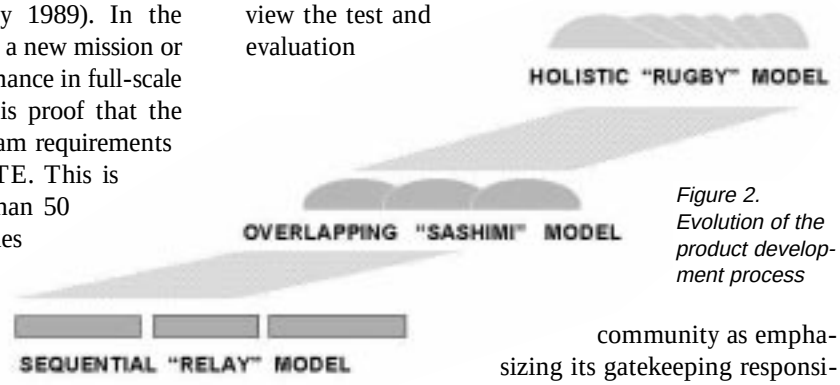

Figure 2. Evolution of the product development process

This change in approach makes imminent sense, and officials should accommodate and legitimize this process in defense acquisition directives. However, this approach creates both a challenge and a heightened need for adherence to basic, time-proven SE/TE principles and practices. Interoperability requirements at the Navy battle group/network-centric level are difficult to define. As with combat system integration 25 years ago, a common set of interoperability design requirements at the battle group/network-centric level does not yet exist.

Defining requirements is a more difficult task at today's frontier, because the acquisition process is geared toward producing *systems*. Users, however, do not want system-level performance: They want warfighting capabilities. The process of translating from system level to actual capabilities defines SE/TE at the battle group level. That process involves several discreet steps conducted iteratively:

(1) understanding the design environment;

(2) establishing system boundaries;

(3) identifying attributes that support program objectives;

(4) establishing the functional baseline by decomposition, data management, interprocess communications, user communications and internal/external communications; and

(5) conducting system requirements reviews. Those involved should never underestimate the importance of each of those steps.

A program-wide commitment

It is crucial that program managers and their government/industry teams share the belief that systems engineering and T&E are not just tools. Together, these two disciplines provide the framework for getting the job done right. Because of current, widespread fiscal constraints, many programs have experienced funding instability. As a result, organizations find it difficult to keep dedicated teams of experts together and focused on worthy projects. Pressure is intense to stay within budget and on schedule for the sake of program survival. In this situation, the discipline of, and commitment to, good systems engineering and T&E suffer greatly.

Unfortunately, shortcuts and other expedient technical and management decisions easily have taken precedence over the iterative process of stepping back in the systems engineering process, where the proper balance of system design is re-optimized. Government and industry program managers can convince themselves that the proof of having met the program requirements lies in demonstrating the system tests' key parameters. They rationalize that this demonstration also will prove that the resulting capabilities will satisfy user needs, and they turn the system over to operational testers and to the user with embarrassing results.

Most striking is that, more than once in the last three years—and despite a stellar 20-year record—some major systems revealed limitations when first operated in a true warfare environment. The reason for these shortcomings, researchers found, was the lack of commitment to good systems engineering and effective, rigorous T&E. Never before has such a large gap existed between what the results of system T&E typically demonstrate and what the actual, full capabilities and limitations of the system prove to be. These results become apparent in fully networked, fully loaded testing of the entire system, when the people, equipment and software operate under true combat conditions.

Perhaps the single most evasive mystery in new systems and capabilities development is determining the necessary amount of SE/TE. The proper level of SE/TE is difficult to ascertain for new capabilities, but it is much more difficult to determine for piecemeal upgrades to existing capabilities. It *must* be difficult, because results borne of developmental and operational T&E illustrate that it is frequently underestimated.

The justification commonly offered for less-than-appropriate SE/TE is that the program's funding level precluded it. That is somewhat of a non sequitur because SE/TE planning and execution should encompass systematic, continuous evaluation of resources. Somewhere along the line, experts involved should have recognized that the programs were not executed in accordance with SE/TE principles and that they should have been canceled or corrected.

Mastering the skills

Many government/industry practitioners have difficulty adhering to SE/TE because they have not mastered its principles or their application. Successful SE/TE practitioners must be competent engineers, economists and managers. As engineers, they must know theory, application, reliability and testing techniques. In addition, they must know how to plan and control a program's fiscal and schedule aspects. As managers, they must communicate clearly with both superiors and subordinates. And, to synthesize and evaluate an entire, complex system, they also must know control theory, computers, modeling and simulation, overall system performance, reliability, producibility, economics, cost/value engineering, optimization, and the treatment of a human in the loop (Shinners 1967).

Building and maintaining an orderly engineering hierarchy is a fundamental key to successfully applying SE/TE in a program. Yet, this tenet frequently is violated, and at significant risk to a program's success. For example, several years ago, approval of the initial T&E Master Plan (TEMP) for the Strategic Sealift ship acquisition program was delayed almost a year because one participant maintained that the two major ship mission T&E parameters were insufficient for monitoring the program's progress.

The program's operational requirements document had quantified the ship's mission in two measures: the ship's average sustained speed; and a 96-hour onload/offload rate for troops and cargo. The partici-

pant, however, requested that items such as rates and lifting capacities for individual loading capabilities (such as port ramps and cargo booms) be included in certain TEMP requirements. The program office preferred to leave those specific requirements flexible, enabling tradeoffs during design and construction. The office did add several parameters to help resolve this issue, but these did not distort the overall requirements hierarchy. If the additions had distorted the hierarchy, they most likely would have driven up program costs and schedule, while driving down overall performance.

Since that time, several ships have been delivered. The Commander of the Navy's Operational Test and Evaluation Force and the Army's Operational Test and Evaluation Agency have performed a successful joint, full-scale, operational T&E exercise, and the program's major customers and stakeholders have agreed that the performance requirements have been met. That is good evidence that the SE/TE hierarchy was the right one.

Personal commitment to SE/TE necessitates an ability and willingness to conduct some very detailed and often tedious engineering work. Even if requirements are well defined, and even if team members are experienced in SE/TE and committed to a project, that commitment can break down over the course of several years in systems development, because the discipline is very difficult and not often glamorous. In today's highly complex and interdependent systems, even small changes can ripple through a heavily integrated architecture.

Conclusions

Systems, capabilities and functions must be partitioned so their designs can be analyzed, tested and upgraded continuously at the lowest practical level. These tasks must be performed without sacrificing overall system performance. Before proceeding to the next integration level, confidence in each subsystem, each function and each capability must be ensured through iterative modeling and testing at each previous design level. When inevitable setbacks occur, such as schedule delays or cost overruns, participants must steer clear of ill-conceived shortcuts in verification testing. The chance that egregious errors and deficiencies will be masked over in higher-level testing is far too great—and so are the consequences.

Just as an individual's commitment to SE/TE can vary over time, so too can the capabilities of organizations, and even industry in general. This fact should be taken into account when program responsibilities are assigned. For example, industries involved in shipbuilding and shipboard combat system development historically have not been asked to invest in, nor tasked to apply, the latest tools at the current highest levels of systems engineering. In the Navy's newest shipbuilding programs, the *San Antonio* (LPD-17) class of amphibious assault ships and in the *Virginia* (SSN-774) class of nuclear powered attack submarines, total ship integrators from industry have been identified—a job previously performed inhouse by the Navy. However, because battle-group-level SE/TE work currently involves a large amount of doctrine and tactics the Navy is still developing, that level of integration is still accomplished by the Navy's inhouse engineering community.

The SE/TE partnership is here to stay. Now, more than ever, a program lacking good SE/TE inevitably will lead to sub-optimized design, and probably unhappy customers. In the not-too-distant future, participants will have mastered SE/TE at today's frontiers. But newer frontiers will be visible then, and more after that. The Navy already is facing challenges beyond battle group interoperability. Systems currently operating in the joint service arena, as well as those in the international arena, are now pushing the envelope. Perhaps the same challenges that systems engineering and T&E currently face will be recognized as keys to success outside the envelope as well. ❑

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References

Blanchard, Benjamin S. 1991. *System Engineering Management*. John Wiley and Sons.

Covey, Stephen R. 1989. *The Seven Habits of Highly Effective People*. Simon and Schuster.

Johnson, Jay, Admiral, USN. April 23, 1997. Address at the U.S. Naval Institute Annapolis Seminar and 123rd Annual Meeting, Annapolis, Maryland.

Meyer, Dan, Captain, USN, and Geary, John, Captain, USN. January 1998. "Aegis Computing Enters the 21st Century." *Naval Institute Proceedings*.

Reynolds, Matthew T. 1997. *Test and Evaluation of Complex Systems*. John Wiley and Sons, 51.

Shinners, Stanley M. 1967. *Techniques of System Engineering*. McGraw-Hill Book Company, 3.

Takeuchi, Hirotaka, and Nonaka, Ikujiro. January-February 1986. "The New Product Development Game." *Harvard Business Review*, as described in "A New Vision for DoD Test & Evaluation," presented by Michael O'Neill, Georgia Tech Research Institute, at ITEA's Annual Symposium, Orlando, Florida, September 17-19, 1997.