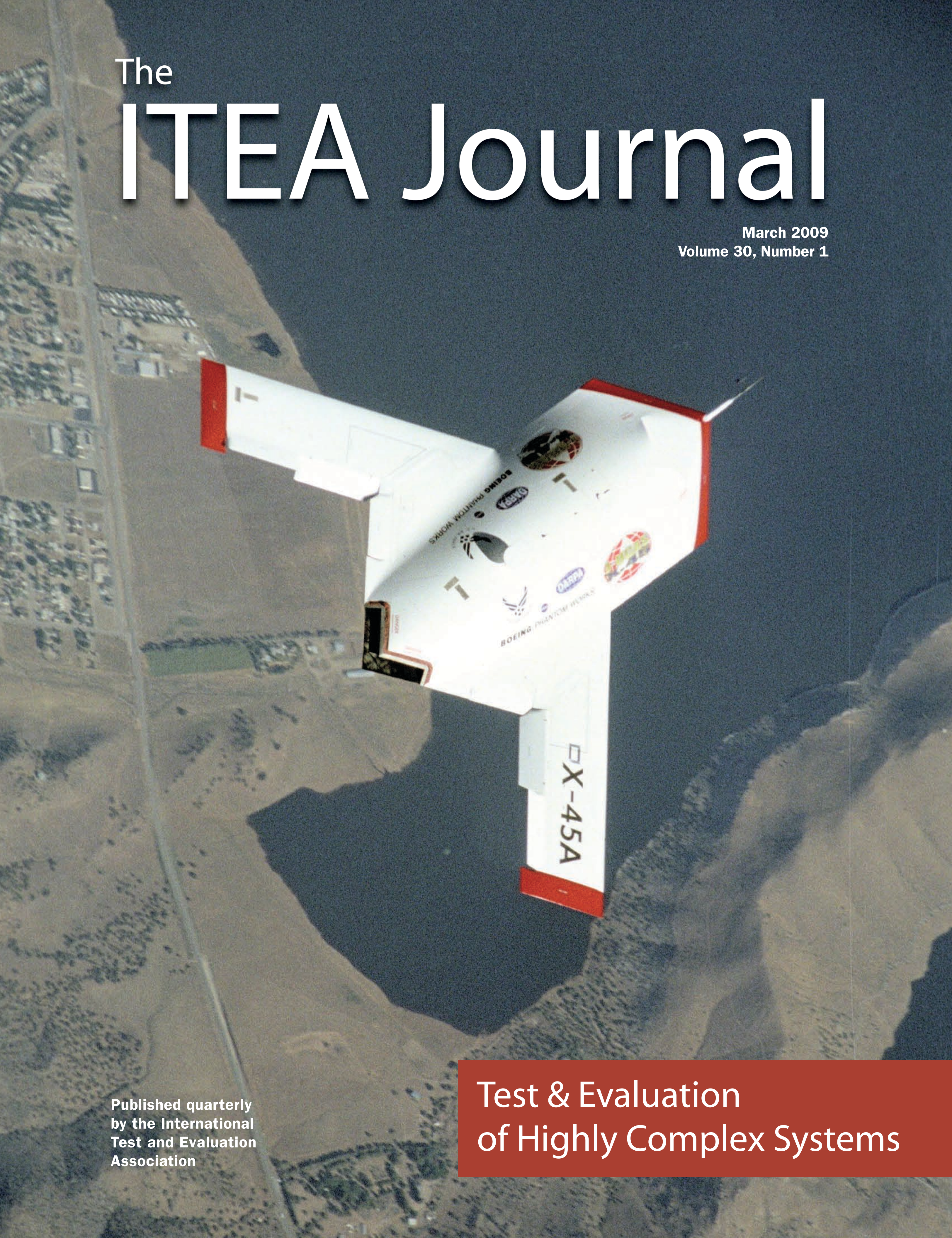

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Test & Evaluation of Highly Complex Systems

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In 2008, the ITEA Board of Directors focused its planning efforts on strategically meeting the evolving needs of the test and evaluation (T&E) community. In 2009, we are continuing to provide mechanisms for organizational growth and moving T&E into the future. The first step was the conduct of the Live-Virtual-Construction Conference in January. The White Sands Chapter has hosted a highly successful Modeling and Simulation Conference for thirteen years. The 2009 Conference contained traditional components of modeling and simulation, but included the introduction of emerging topics of interest concerning testing in a Joint environment. The second step was our very timely and relevant one-day seminar in February, *Future Defense Spending and the Implications for Test & Evaluation: The impact of the economic downturn and the change of administration on defense system acquisitions and the Test & Evaluation space*. The seminar examined possible impacts of the economic down-turn and President Obama's emerging national security agenda on DoD's major acquisition and T&E missions. Speakers discussed views on how the T&E community can provide value-added support as federal budgets decline, pressure increases on DoD to reduce the acquisition and life cycle costs of major defense systems, and the Obama administration initiative for a new National Security Strategy is implemented.

One result of our plans to revamp ITEA in order to meet the strategic goals of the organization is evident in the dramatic change in this March 2009 issue of the Journal—beginning with the graphic front cover. The redesign is actually the culmination of an internal and external facelift that began in March 2008. The timing was chosen to coincide with the 25th anniversary of the Journal, which was initiated in 1984. You may have noticed small changes to the Journal over the past year—changes to provide a more professional appearance, to make articles consistent both within an issue and from one issue to the next, and to improve the readability of articles. The size of the issues has consistently increased, partially due to ITEA event organizers encouraging presenters to produce full papers which are immediately considered for publication. I urge you to take the time to peruse the 2009 Journal themes on the ITEA website and on page 29 of this issue and consider contributing a paper in the future. As an educational organization, the Journal plays a large part in disseminating relevant, timely information to our members.

Our mission is to make *The ITEA Journal* the leading archival publication for T&E developments, technology, emerging needs, and member activities. As such, the theme for this issue is "Test and Evaluation of Highly Complex Systems". The growing complexity of systems challenges every aspect of T&E, from facilities and instrumentation to test processes and management to data collection and analysis. Our current test environment is being asked to accommodate joint and distributed testing, chaos and complexity theory, emergent behaviors, virtual testing, modeling and simulation, cognition and autonomy, and the assessment of mission effectiveness from individual human, component, and system performance. I hope that this issue will help you to fully understand the resulting impacts and challenges to current and future T&E.


John Smith

A challenge that we continue to face is effective integration of the T&E and training communities. A new charter for the Defense Test and Training Steering Group (DTTSG) was signed in January. The purpose of the DTTSG is to oversee areas of common interest to the T&E and training communities. The Group is co-chaired by the Under Secretary of Defense for Personnel and Readiness and the Director, Operational Test and Evaluation, with membership from the Vice Chiefs of the Services, Under Secretary of Defense (Acquisition, Technology & Logistics), Under Secretary of Defense (Intelligence), Assistant Secretary of Defense (Networks Information and Integration) and Director, Joint Staff. The DTTSG serves as a decision making forum to resolve issues concerning policy, programs, legislative direction, or business processes that are common to the Department of Defense's test and training activities. Test and training integration is obviously important to our senior leadership. ITEA will strive to track and address the challenges and successes associated with the T&E and training communities working together to ensure cross-efficiencies and cross-utilization of the Department's resources. As such, the George Washington Chapter is hosting *Change-Change-Change for the 2020 Vision: The Test and Training Open Forum* on 22–25 June in Williamsburg, Virginia. This forum is the second in an ITEA series on testing and training, and directly focuses on opportunities provided by the new administration, new policies, and new directions. It is intended to bring the test and training communities together to find shared opportunities in one of the training community's population centers.

The Board of Directors' efforts to revise ITEA's Strategic Plan and its implementation components, as necessary, is underway to ensure that the future of ITEA is aligned to meet the needs of the T&E profession and its technology advancements in the years to come. The step-by-step process began with a kick-off session in December followed by an intensive two-day strategic planning session in February. The Board Members are re-visiting the current mission and vision of the organization and ensuring that ITEA's Strategic Plan includes measurable goals that link to the established strategic vision. Stay tuned for more information as we engage in this important process.

John Smith

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Test and Evaluation of Highly Complex Systems

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I have been working in Army test and evaluation (T&E) since 1974 and have seen enormous increases in the complexity of systems since I first started in the business. Systems in 1974 were largely stand-alone, analog, and mechanically controlled. Now to conduct and win the next major conflict with a conventional enemy or against violent extremist movements, previously unimagined systems are being developed and fielded to our warfighters. The complexity of these new systems is a result of addressing today's and tomorrow's threats with more accurate, lethal, reliable, survivable, interoperable, and maintainable systems. Most of today's systems are very software intensive and network enabled, and have on-board, complex subsystems. The complexities that often arise are a result of the interactions among the systems and subsystems, and as a result, they cannot be tested and evaluated in isolation. These systems are vital enablers that assist the warfighters in accomplishing their missions. These new systems are often a system of systems (SoS) on a single platform such as the mine-resistant ambush-protected (MRAP) vehicles or a family of systems such as the Future Combat Systems (FCS), the Stryker family of vehicles, or the Ballistic Missile Defense System.


Dr. James J. Streilein

Testing and evaluating a single service or a joint SoS or a Family of Systems (FoS) requires combat and materiel developers, testers, and evaluators to form larger and more diverse Integrated Product Teams (IPT) and Test and Evaluation Working Integrated Product Teams. These teams must establish and refine the system's requirements, and properly establish and scope the resources and events required to determine the capabilities and limitations of the SoS and/or the FoS under test. In most cases, the SoS or FoS are expensive to produce, train, maintain, and sustain. The cost to properly test and evaluate these systems can run into many millions of dollars. Because of the Service's desire to fill a capability gap and the system's development and production expense involved, many new systems have increased visibility from the requesting Service and are normally designated by the Department of Defense as a program requiring the oversight of the Director, Operational Test and Evaluation and Developmental Test and Evaluation. This DoD oversight expands T&E complexity, IPT membership, coordination, documentation, planning, resources required, and the program's schedule.

The Army Test and Evaluation Command (ATEC) uses a number of processes and best practices to T&E SoS and FoS per the policy and guidelines directed in the June 2007 Office of the Secretary of Defense Section 231 Report. Some of the challenges for the command in implementing the guidance found in the Section 231 Report are to maximize the use of mission-based test and evaluation, Modeling and Simulation (M&S), joint and distributed testing, reliability growth testing, and determining system interoperability (subsystem, system, and with multiple systems). Let's discuss a few of these challenges.

What is mission-based T&E? Mission-based T&E (MBT&E) is an emerging process to focus T&E of a SoS or a FoS on a system's mission contribution as intended by a combatant commander in accomplishing their assigned mission. This requires the evaluation team's assessment to not only address whether a given system's functionality was sufficiently demonstrated per the critical operational issues and criteria, but to also ascertain for the users and combat developers the likelihood that the SoS or FoS will improve the unit's ability to successfully accomplish their mission. The T&E strategy must do more than check a system's capabilities against the standard type of requirements; now the mission capabilities must also be outlined and a crosswalk developed to ensure that the test events and data will address both system and mission capabilities. However, mission success is often determined by qualitative assessments (military judgment) versus SoS and FoS performance specifications, which are often determined by quantitative data. The determination of whether a system can successfully maneuver over a specified type of terrain or operate in a cold or hot environment is easily tested and quantitatively verifiable, but determining whether the system capabilities assist commanders in accomplishing their mission—given the many mission types and threats that exist—is more of a challenge for the T&E community. It is not feasible to test to each mission scenario. Moreover, it will not be practical to test enough replications of the missions and threats to the sample size needed to determine the system's performance with statistical significance. We are led to employ M&S to address mission capabilities, but M&S brings it own level of complexity.

When using M&S to determine system capabilities, its selection as an element of the T&E strategy must also take into consideration that verification, validation, and accreditation must be obtained before M&S is utilized to support an acquisition milestone decision. When M&S is used early in the system's development, it can assist the program manager and contractors to enhance the design. When testing the MRAP, M&S helped to characterize the vulnerability and the survivability of the system. This reduced the time required to develop and test the system.

M&S is a key enabler for effectively focusing and executing T&E. It provides a practical means to support system development, combat development, and T&E throughout complex system program development. M&S helps to prioritize live testing, characterize system attributes, provide information about system performance under conditions that cannot be practically measured with live testing, and reduce overall program risk. Validated M&S expands the test envelope beyond traditional methods required to test today's complex systems. M&S can be used to predict system performance, identify technology and performance risk areas, and support the evaluation of the system's effectiveness, suitability, and survivability.

As we all know, live testing of today's complex systems is becoming increasingly unaffordable. There are many impacts and interactions of adding new equipment to the current force that must be considered and evaluated. In addition, there is limited availability of complementary and adversary systems and forces. M&S surrogates for these systems and forces can effectively flesh out the battle space for live tests. Test range limitations, such as size, availability, cost, security, safety, and environmental concerns must also be taken into consideration. Testing will never be completely physical because of size, complexity, and interoperability requirements that will demand a synthetic environment to be wrapped around the test unit. M&S provides controllable, repeatable testing of components, software, and hardware throughout the acquisition cycle. M&S can provide a defendable, analytical underpinning for decisions.

The model-test-model approach is often used by ATEC throughout the acquisition life cycle to effectively focus T&E resources on critical test issues. M&S is used to provide early predictions of system performance. Based on those predictions, tests are designed to provide actual data to confirm system performance and validate or accredit M&S. Early in the acquisition and before final configuration hardware is available for testing, M&S can be used to support engineering-level trade studies of technologies and systems and provide data to both the system development and evaluation. Testing M&S can range from computer-based simulations to virtual, wrap-around simulations to hardware-in-the-loop physical testing of components, subsystems, and systems. As hardware matures and becomes available, the evaluation will begin to focus on empirical test data, rather than on the M&S representations. M&S and T&E do not replace each other, they complement each other. The iterative and integrated use of M&S with T&E is of greater value than M&S and T&E conducted in isolation.

Determining system interoperability is also a challenge. Two types of system interoperability must be proven out before fielding: (1) system interoperability where the system's software and hardware can exchange information effectively and (2) the SoS or the FoS exchanging information with existing Army, Joint, and multinational systems and units on the battlefield. The cost of testing interoperability is high. Assembling the architecture needed to test the system's interoperability requires a great deal of hardware and personnel for an extended period. Often testers piggyback on Joint and Service exercises to defray the cost of testing. Using exercises provides test articles and personnel, but testers can lose control of the test event and place their data needs at risk. The primary focus of exercises is not to determine the system capabilities under test or mission success, but to train staff and forces, as well as evaluate plans and strategic operations. Therefore, the scope to determine interoperability must be designed and robust enough so that the service operational test agencies and the Joint Interoperability Test Command can evaluate and certify that the system can generate, deliver, use, and consume data between platforms or systems.

Lastly, the June 2007 Section 231 Report stressed that integrated developmental and operational testing should be used whenever possible to maximize use of all data. This is all the more difficult for complex systems. However, to conduct a single event to collect both developmental and operational data, the event must not conflict with Title 10 independence of operational testing for materiel developers. If the design and execution of a single test event can support a milestone decision, the test must be engineered so that program managers may still receive an assessment that the system is mature enough to successfully execute missions against realistic threats in operational conditions. A separate event may eliminate the ability to conduct test-fix-test events because the warfighters may not be kept for testing until a fix is developed and applied to the system. Some separate developmental testing (DT) is needed to address the entrance criteria for operational testing (OT) and provide a safety release. Although every effort should be made to conduct DT with operational realism, the IPT may find it difficult to execute only one integrated DT/OT event to evaluate complex systems.

Budget constraints dictate that we make maximum use of T&E resources by combining OT with DT whenever practicable. A single test event for OT and DT has the potential to answer both DT and OT questions efficiently in terms of the time and resources normally required, but it is also the most difficult to execute because it requires maximum coordination and cooperation among members of the test community. When collection of DT and OT measures are integrated, there must be cooperation where all parties stand to benefit. However, more complex systems often have more measures to test and evaluate. The developmental test team, operational test team, and evaluation team must develop a test management structure to share control of the event. When different test agencies participate in the same test event and exchange data, a two-level common language is often required. This language includes terms used to talk about T&E, such as, "issue," "mission," and "measure," as well as language used for evaluating a specific system, such as, "detection," "slant range," and "slant angle." A common language requires standard data definitions and formats while enforcing the specific definition of variables and conditions, and interpretation of results. If the goal of testing is to predict how a system will perform under different conditions, an experimental design must be used that accommodates the needs of both the developmental and operational testers.

For complex systems, the increased number of factors and conditions that are represented across multiple DT and OT data collection phases increase the breadth of the evaluation and the number of questions the evaluator can answer. Metrics that were collected in different event phases (e.g., through both DT and OT) and are complementary to each other might be analyzed together, increasing sample sizes and the confidence of the test results. OT experimental designs might be designed such that they return DT relevant information and provide useful feedback to the developers. The results of free-play testing should be carefully documented and then analyzed to extract metrics that can be analyzed in concert with, or in addition to, DT metrics. Structuring the factors and conditions such that DT and OT issues are addressed is paramount for a successful test.

We have addressed a few processes and best practices that should be considered when testing a SoS or a FoS system. There are others, but the effectiveness and efficiencies or processes or practices must be explored by the IPT and working integrated product teams.

There are many challenges for the SoS and FoS test and evaluation teams to ensure that they properly determine the system's performance while implementing the principles cited in the DoD Section 231 Report. The teams must remain innovative and use techniques such as MBT&E, cost effective instrumentation, accredited M&S, and optimize resources such as test participants, ranges, and test events. Success in fielding equipment to our warfighters will continue to require total commitment, coordination, and cooperation of all members of the acquisition communities. I have seen the T&E community continually improve over the years since 1974, and I look forward to our efforts and innovations to handle the increases in complexity of systems to be tested and evaluated in the future. ❑

DR. JAMES J. STREILEIN entered his current position in April 2007. As the executive technical director/deputy commander, U.S. Army Test and Evaluation Command, he provides oversight and technical direction to all command efforts to include testing, evaluation, modeling and simulation, and instrumentation. He serves as commander in the absence of the commanding general and as the Army member of Technical Advisory Board for Joint Test and Evaluation. He is directly responsible for the Army Quick Reaction Team's work. ATEC is a multibillion dollar command with over one third of all Army land and is currently conducting developmental tests, operational tests, live fire tests, and field data collection on over 400 systems in normal acquisition and over 200 systems in rapid acquisition. He represents ATEC in dealings with program managers, program executive officers, Department of the Army, other services, Joint Improvised Explosive Device Defeat Organization, Office of the Secretary of Defense, Defense Science Board, Army Science Board, National Defense Industrial Association Committee on Operational Test and Evaluation, etc.

In September 1999, the Army reorganized test and

evaluation, and Dr. Streilein was selected as the first director of the newly formed Army Evaluation Center of the Army Test and Evaluation Command. The Army Evaluation Center is the Army's lead for its technical and operational evaluation mission. In the 1996 reorganization of Army test and evaluation, Dr. Streilein was selected as the first director of the Evaluation Analysis Center of the Operational Test and Evaluation Command. Dr. Streilein became a member of the Senior Executive Service in August 1991 upon selection as the chief, Reliability, Availability, and Maintainability Division of the U.S. Army Materiel Systems Analysis Activity, where he began working in 1974. He received the Presidential Rank Award—Meritorious Executive, 2005; Decoration for Meritorious Civilian Service 1987 and 2007; and Army Superior Unit Awards, 2000 and 2004. He received a bachelor of science degree in mathematics from Carnegie Mellon University and a doctorate in mathematics from Pennsylvania State University.

Invited Article

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Test and Evaluation and the ABCs: It's All about Speed

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When Lt Gen Charlie Croom took over as the Director of the Defense Information Systems Agency (DISA) in July 2005, he brought us a new message: "It's All about Speed." What he meant was simply this: It takes us too long to get new capabilities into the hands of the warfighters. When he retired this past summer, 3 years after his arrival, he left a legacy of change—of innovation—in how we acquire and test information technologies (IT) in DISA.

Key words: Acquisition; adopt-buy-create; capability T&E; information technology; scalability of performance; scalability of support; interoperability; security.

General Croom was right. My experience with acquisition and testing of information technologies began in 1998 on my arrival in the Army Test and Evaluation Command and my assignment as Evaluator for one of the Army's "digitization" systems. Six days after my arrival, I found myself at Ft. Hood, Texas, seeing the new capability for the first time. I was amazed at this new system and wished I'd had it in my units way back when. Six *years* later, we hadn't managed to get that system through the acquisition process, had not even completed the Initial Operational Test and Evaluation (IOT&E). It took the operational necessity of the second Gulf War to get that system into units other than the test unit. And when we did that, we had to spread the few systems we had for testing out to those other units and didn't give them the luxury of time to do a lot of training. But what a remarkable difference that Blue Force Tracking system made for the warfighters.

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There are many reasons why we took more than 6 years to field the system; hindsight suggests to me that none of them was particularly good. There were other ways to develop, test, and field the new system; we just didn't look "outside the box" of DoD 5000 to find them. That's the message General Croom brought to Defense Information Systems Agency (DISA). When he looked at how industry, especially companies like Google, eBay, Amazon, and Travelocity, just to name a few, brought new capabilities to its customers in short cycles—with speed—he asked why the Department of Defense (DoD) couldn't do the same. The fact is, we can, but it requires some fundamental changes in acquisition philosophy. It is time that we took a hard look at how we acquire and test information technologies in the DoD.

Adopt—buy—create

Shortly after his arrival, Lt Gen Croom cast his message of speed in these terms: "Adopt before Buy, Buy before Create"—the ABCs. It was a simple message; to speed up the process of getting enhanced capabilities into the hands of the soldiers, sailors, airmen, and marines that need them, we would look first for something already available in the Department—say an Army system for example, that would satisfy a need identified by the Navy—and adopt it for fielding to the entire Department. If there was no capability already fielded, then we would look for a commercial product—maybe even "the 80% solution"—and buy it for fielding to the Enterprise, then add capability in short cycles. As a last recourse, we would create it; last because that approach comes with a lot of program management overhead, cumbersome decision-making processes, and sometimes heavy-handed oversight, not to mention lengthy periods of development and testing—processes that are slow to move and adjust when it's all about speed.

There were other innovations in this new acquisition paradigm. One notable innovation was to bring competition into the acquisition process; the theory being that if there is more than one provider of a capability, and those providers make money based on product use within DoD, then competition for market share will motivate those providers to continually improve their products and entice more users to their

Table 1. Test and evaluation for the ABCs

IT acquisition strategy	Capability maturity/risk	Critical T&E issues
Adopt	Capability in use in Department of Defense	Scalable performance and support
Buy	Capability in use in commercial sector	Scalable performance and support Secure Interoperable
Create	New capability to be developed	Scalable performance and support Secure Interoperable Effective, suitable, survivable

side. It's an interesting idea that DISA has put to the test, and we are starting to see it work in the Net Centric Enterprise Services (NCES) program.

Those of us in the test and evaluation (T&E) business need to hear, loud and clear, the message of speed because we can ill-afford to be an obstacle in the path of bringing capability improvements to the warfighters. Instead, we need to be an *enabler* in the process that ensures rapid delivery of effective, suitable, interoperable, and secure information technologies. That type of agility can only occur when we are involved from the beginning. In some commercial circles, they refer to this as "test driven development."

T&E for the ABCs

The ABCs present an opportunity for innovation and invention in T&E. Once we have identified a capability need, through what is now the Joint Capabilities Integration and Development System (JCIDS), the program manager formulates an acquisition strategy. For an IT system, the acquisition strategy is essentially a choice among the ABCs—adopt what's available already, buy it, or create it. Likewise, we should have a T&E strategy that corresponds to the ABCs.

If the acquisition approach is to adopt something already available in the DoD, then that capability has presumably negotiated all of the acquisition and T&E wickets to achieve its fielding decision. More specific to T&E, that capability has already been determined to be effective and suitable for its intended use. As a capability proposed for the enterprise, however, there are two relevant issues to resolve before full deployment:

- scalability of performance (Does the capability still perform at acceptable levels under greater use at the enterprise level?),
- scalability of support (Is there sufficient capacity for supporting the capability at the enterprise level, such as help desk capacity?).

There may be other considerations, but the motivation behind the adopt strategy is to accept the risk and make an existing capability available to a broader user base.

In the case of the "buy" approach, the premise is that we have identified a commercial product that satisfies all or part of the need identified in JCIDS. The product is already in the commercial marketplace, but more specifically to T&E, it has satisfied unit and functional testing by the vendor. If we accept the capabilities and limitations of the commercial product as is, then the remaining issues for us to verify prior to use in the DoD environment are:

- performance and support at the enterprise level,
- interoperability with other DoD systems or services,
- security (information assurance).

Focusing T&E resources on these areas will permit rapid assessment and recommendations for the acquisition decision makers.

In the case of the "create" approach, no existing capability in the Department or commercial sector satisfies enough of the identified need. In this case, the capability must be developed, and T&E will have to answer all standard evaluation concerns. *Table 1* summarizes the T&E concept for the ABCs.

However, the create approach must not be "business as usual" for DoD acquisitions. The key for IT acquisition is to bring new capabilities forward in small, warfighter-relevant increments, or "sprints." In the commercial sector, some refer to this process as "Agile development." There is a wealth of information available about agile processes, so I will not attempt to describe it in detail here. At the core of this process, however, is the idea that a small team of developers, users, and testers work together to define, build, test, and field new capabilities in short cycles—"build a little, test a little, field a little" as General Croom would say. To field the system, we would start small and scale rapidly, with T&E monitoring to ensure capability effectiveness as use scales upward.

There are some fundamental differences in the ABC approaches when compared to current acquisition

Table 2. Test and evaluation in the Department of Defense acquisition process

Activity	Test agent	Conditions	Customer	Reference
Developmental T&E	PMO/contractor/ government DT organization	As determined by PMO; generally benign, lab; developer personnel	PMO	DOD 5000
Operational T&E	OTA	"Operationally realistic,…, typical users"	MDA	Title 10 DoD 5000
Joint Interoperability Test Certification	JITC	"Applicable capability environments"	J6	DODD 4630.5 DODI 4630.08 CJCSI 6212.01D
Security T&E (IA Certification & Accreditation)	OTA, DIA, FSO, NSA	Operational, lab	DAA	DoDI 8510.01 DIACAP*

PMO, Program Management Office; DT, Developmental Test; OTA, Operational Test Agency; MDA, Milestone Decision Authority; JITC, Joint Interoperability Test Command; J6, Joint Staff J6 is Director for Command, Control, Communications, and Computer Systems; DoDD, DoD Directive; DoDI, DoD Instruction; CJCSI, Chairman Joint Chiefs of Staff Instruction; IA, Information Assurance; DIA, Defense Intelligence Agency; FSO, Field Security Office (DISA); NSA, National Security Agency; DAA, Designated Approving Authority; DIACAP, Defense Information Assurance Certification and Accreditation Process; DOT&E, Director, Operational Test and Evaluation.
* Note also the DOT&E Policy on testing IA during OT&E. DIACAP C&A does not complete the requirement for IA testing.

practice. The ABC model accepts risk, whereas our traditional model is founded on risk aversion. The current scheme of acquisition milestones are not a good fit in the ABC model—the ABC acquisition process is too fast. Our traditional acquisition decision-making processes may need to change; for example, in this model, there would be no full deployment decision review. Likewise, our T&E practices should adjust. For example, in none of the T&E approaches suggested is there a concept of a large-scale IOT&E or Capstone event. For IT systems, the IOT&E as we think of it today is an obsolete practice.

None of this suggests we eliminate oversight or testing. Each has a critical role, but we should acknowledge that the processes we've built and put in place for the past decades, and which have always been focused on major defense systems such as tanks, ships, and planes, may not be well suited for the agile IT environment. We should look to the commercial IT sector and pull their good ideas into the DoD. And we should teach innovative IT acquisition concepts, such as agile development and test, to our program managers and testers as part of our formal acquisition curriculum.

T&E for better decision making

There are at least four different test and evaluation activities that support different decision-making processes for information technologies, but the question is, do the four activities improve our *acquisition* decision-making process? The T&E activities include

- Developmental Test and Evaluation (DT&E)
- Operational Test and Evaluation (OT&E)
- Joint Interoperability Test and Certification
- Security Test and Evaluation (Information Assurance Certification and Accreditation)

We do each of these tests for different purposes, and that is certainly understandable. What is not understandable is why these tests are performed under different conditions, by different test agents, for different customers. Developmental testing, for example, helps the program manager find and fix problems, ensure compliance, and improve production processes. It tends to be more technical than operational. Robust DT helps ensure readiness for OT. OT, on the other hand, ensures readiness for fielding. Why doesn't DT ensure readiness for fielding?

Interoperability and security testing are more specialized and feed other decision-making processes, i.e., Joint Interoperability Certification and the Defense Information Assurance Certification and Accreditation Process. Unfortunately, we do not treat these two processes as integral to acquisition decision making, which results in situations in which the Milestone Decision Authority might approve a decision to buy for the Department, while the Designated Approving Authority (DAA) may not authorize its operation on their network. *Table 2* summarizes the T&E landscape for IT.

Our acquisition decision making would be much improved if the various T&E activities fit into a holistic model. Recent emphasis on "integrated T&E," such as written in the December 22, 2007, memorandum signed by the Director of Test and Evaluation and the Under Secretary of Defense for Acquisition, Technology, and Logistics, acknowledges the importance of early involvement of the test community, but does not do enough to eliminate the barriers that exist between test activities or compel streamlined T&E.

Capability test and evaluation

In DISA, we are working to unite all test activities into a holistic, coherent T&E model. We refer to this model as capability T&E (CT&E). For capabilities being developed in sprints, having four different organizations doing the testing at different times, under different conditions, and writing different reports is laughably inefficient. The commercial sector would never do this.

To the extent possible, we would like to designate a capability test team (CTT) to plan and conduct CT&E events. All CT&E events are a shared resource. To ensure agility in T&E, CT&E events are *risk-based*, according to which ABC acquisition approach is used. For each sprint there is one CT&E event. CT&E can be thought of as a "one team, one time, one set of conditions" approach to T&E. Upon completion, the CTT writes one report for use by all decision makers: the milestone decision authority, the interoperability certifier, and the DAA. One means to obtain buy-in for this concept would be to have all of these decision makers sign the T&E master plan (TEMP).

To ensure acceptance by all decision makers, CT&E test designs must also be *mission-focused*. During the CT&E, typical users exercise the capability under test, similar to beta testing in the commercial sector, and are supported as intended when fielded. The combat developer, part of the CTT, defines and validates the scenario and mission threads. The test conditions replicate the operating environment, leveraging distributed live, virtual, and constructive capabilities, such as the Joint Mission Environment Test Capability (JMETC), to the maximum extent possible. CT&E therefore expands on and puts into practice the concept of "integrated T&E" by including all stakeholders in developing the test strategy at the beginning of the acquisition process and by structuring *all* test activities as shared resources.

Some organizations will see CT&E as an infringement on their independence. There is nothing about the CT&E concept that precludes CTT members from performing independent evaluation. In fact, the CT&E construct works best when all stakeholders have their say. The TEMP should reflect the ABC strategy being followed and describe the CT&E events designed to ensure that critical issues are adequately addressed. Once approved, the CTT executes.

We can fundamentally change the way we acquire and test information technologies in the Department. By focusing on small improvements to capability, development cycles in sprints, and a one team, one time, one set of conditions T&E model, we can simultaneously reduce time to fielding while improving product quality. After all, it's all about speed. ❑

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Improving T&E Processes for Highly Complex Systems

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Kudos to the leadership of ITEA for tackling a seemingly intractable problem—the test and evaluation of highly complex systems. One of the most challenging areas confronting the Department has been the timely development and deployment of next generation command and control systems as well as enterprise resource management systems. For several years, the developing agencies have attempted a variety of initiatives intended to make the acquisition of software intensive systems more agile. Despite the best efforts, major Command and Control (C2) and Enterprise Resource Program (ERP) systems have consistently encountered significant challenges that have delayed successful fielding. Too often, these problems manifest themselves when systems fail to perform as expected in the final stages of developmental testing or in operational testing. This raises the question, how can we in the T&E community improve our processes so that the investment in T&E provides the greatest return to both the warfighter and the taxpayer?

William J. McCarthy

In reviewing the root causes of these problems, several points have emerged. First is the need for clearly articulated requirements. Too often, the requirements are not well defined. Documents such as the Capability Development Document (CDD) are sometimes not completed until the development is nearly completed. While there is a legitimate concern that the documentation process not impede development of products needed by the warfighter, it should be evident that no one's interests are served when the gaining Service and the developing agency are still addressing substantive differences in perceived requirements during Systems Integration Testing. Not only must the contractor understand the desired performance, to be successful, the contractor must also understand the intended operational environment and the legacy systems that will interface with the new system. If the developing agency does not understand what is to be delivered, it is unrealistic to expect the contractor to understand.

As the Department has moved to Internet Protocol (IP) based solutions, some developers have essentially assumed away the transport layer, not recognizing that the military implementation will literally span the globe and include both satellite and terrestrial links, extensive cryptography, and ultimately disadvantaged users who will be obliged to work with comparatively limited bandwidth. Failure to understand the intended operational environment has led government program managers to accept industry proposed Commercial-Off-The-Shelf solutions that were never intended to deal with the latencies seen in the actual architecture. In a recent operational test, distant users found three of ten applications timed out waiting for responses that were delayed due to transmission latency. Discovering such problems in operational testing highlights the need for realistic developmental testing that is informed by an understanding of the likely operational environment. Developmental testing that is constrained to a set of distributed laboratories operating on terrestrial fiber links is not necessarily a representative environment. While it is technically possible to emulate satellite delays and disadvantaged users, developers frequently overlook this step. A related problem is the lack of detailed data available to permit developers to realistically model current network performance.

A third major challenge has been a lack of structured development. In an effort to become more agile, developers have been encouraged to focus on small modules of usable software that can be developed in a certain period of time. This, in itself, is a sound practice that can help avoid the situation where the 95 percent solution is delayed indefinitely while seeking the last 5 percent of performance. However, taken to the other extreme, it can result in a software module that has little or no operational utility. Such an outcome was seen in the development of the five pilot capability modules for a major DoD program. While the requirements for the modules were articulated by the user, the developer was allowed to shift individual capabilities to future spirals without further reference to the user. This time certain approach can lead to on time deliveries of software that fails to meet user needs. We tend to overlook the fact that there are indirect costs in training and productivity associated with each fielding event. Undue emphasis on only building what can be completed in a narrow window (6–12 months) can lead to the continual deferral of the most difficult problems. There is no incentive for a program manager to attempt to solve a long term problem if his or her measure of success is solely on time delivery of semi-annual or annual updates.

An unintended consequence of this unstructured approach is often the introduction of additional defects into the delivered software product. As industry leading experts such as Watts Humphrey from Carnegie-Mellon have pointed out, each time a developer goes back into the code to re-engineer a feature, additional defects are introduced. This is not just an efficiency issue, it is a security issue. A structured approach that addresses required functionality the first time allows for the most robust verification executed by the most knowledgeable individuals early in the development process. The complexity of today's software makes a thorough verification by individuals who did not generate the original code virtually impossible in the latter stages of development. Thus we find systems that pass Functional Qualification Tests, only to have 25 or more major software defects discovered during system level testing.

There are no simple solutions for software intensive systems. Even the most rigorously tested systems have encountered unforeseen difficulties in implementation. The path to success is remarkably similar to complex hardware systems: clearly articulated requirements, a disciplined systems engineering approach and realistic developmental testing that reflects an understanding of the actual operational environment.

The good news is that the Department has recognized all three points and is taking positive action. The recent publication of Department of Defense Instruction 5000.02, as well as, the Systems Assurance Guidebook and revisions to the Defense Acquisition Guidebook have all emphasized these principles. Outside the Beltway, Joint Forces Command's leadership in articulating the warfighter's requirements has been critical to the development of the revised way ahead for the Network Enabled Command Capability (NECC) program. Within DOT&E, we have allocated four of our new action officer billets to provide dedicated personnel to participate in the JCIDS process. These individuals provide the requirements community with insight into the development of "testable" requirements and metrics that will indicate whether a system has a reasonable probability of meeting its requirements at fielding. Areas where the T&E community can assist are in the rapid implementation of these policies; the development of improved instrumentation to better measure system performance with minimum impact and the development of enhanced modeling and simulation to support more realistic testing earlier in the process. There are no PowerPoint solutions for these challenges; however, with the hard work of the entire acquisition community, we can ensure that we deliver operationally effective and suitable systems to our warfighters at minimum cost to the taxpayers. ❑

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Physiological Sensor Suite Using Zero Preparation Hybrid Electrodes for Real Time Workload Classification

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Quantum Applied Science and Research is working closely with the Aberdeen Test Center to develop an integrated system to monitor warfighter physiology. This need has been recognized by two recent major programs: the Defense Advanced Research Projects Agency's Augmented Cognition program and the U.S. Army's Warfighter Physiological Status Monitor program. However, these programs were limited by inadequate development of fully deployable noninvasive sensors and in the number of physiological variables they could simultaneously measure.

Warfighters need to rapidly perceive, comprehend, and translate combat information into action. To aid them, robust gauges have been developed for classification of cognitive workload, engagement, and fatigue, which simplify complex physiological data into one-dimensional parameters that can be used to identify a subject's cognitive state during the varied tasks carried out in a training environment.

This article describes the two main hardware modules that form part of an integrated Physiological Sensor Suite (PSS): a Physiological Status Monitor (PSM) and a module for the measurement of electroencephalograms (EEGs). The PSS is based on revolutionary noninvasive bioelectric sensor technologies. No modification of the skin's outer layer is required for the operation of this sensor technology, unlike conventional electrode technology that requires the use of conductive pastes or gels, often with abrasive skin preparation of the electrode site.

The PSS was designed to be wearable and unobtrusive, with an emphasis on the capability of long-term monitoring of physiological signals. These factors are of considerable importance in operational settings where high end-user compliance is required. The PSM is a simple belt that is worn around the chest. The EEG system has already been incorporated into a soldier's Kevlar helmet and tested successfully during combat training.

Data are acquired using a miniature, ultralow-power, microprocessor-controlled multichannel data acquisition (DAQ) unit that transmits data wirelessly to a base station/data logger worn by the subject. The DAQ unit is worn on the body close to the measurement point, reducing the amount of cable clutter and minimizing the impact on subject mobility without introducing motion artifacts.

Hardware

Hybrid biosensors

Electrophysiological measurements in the PSS are performed using hybrid (capacitive/resistive) bioelectrode technology. An electrocardiogram (ECG) sensor of the type used in the PSM is shown in *Figure 1*.

The EEG module uses hybrid sensors that are capable of measurements of through-hair EEG *(Figure 2)*. Electrical contact is made via a set of "fingers," each of which is small enough to reach through hair and make electrical contact to the scalp between hair follicles. The inner circular section is sprung to follow the head contour.

Electrophysiological measurements using hybrid bioelectrodes are enabled by a proprietary common mode follower technology. The common mode follower is used as a reference for the biosensors so that the common mode signals appearing on the body are dynamically removed from the measurement, typically achieving a common mode rejection ratio of 50 to 80 dB.

Physiological status monitor

The PSM *(Figure 3)* measures ECG signals, body temperature, respiration data, body position, and actigraphy. Proprietary ECG and acceleration/respiration/temperature sensors are incorporated into a belt worn around the chest. The outputs of the ECG and acceleration/respiration/temperature sensors are combined to determine the health status of the subject.

The Gain/Filter module acquires the ECG and acceleration/respiration/temperature data, stores it on a FLASH card, and wirelessly transmits the data via an

Figure 1. Hybrid electrocardiogram biosensor (with a U.S. 25 cent coin for scale).

ultralow-power wireless link to a local base station. The system is easy to install and use and operates for several days from a single AAA lithium ion battery.

EEG sensor harness

The EEG harness shown in *Figure 4* fits under the Kevlar helmet of a soldier. Sensors are positioned at the nominal CZ, C3, C4, FZ, F3, F4, PZ, and P4 10–20 array positions. The array is anchored to a standard helmet harness, and a mechanical isolation system isolates the array from the helmet motion during strenuous activity. The harness and Kevlar helmet have been worn without discomfort for periods of up to 3 hours by solders performing combat tasks.

Miniature low-power data acquisition unit and base station

The DAQ unit was designed to address the general requirements for multichannel EEG, ECG, electro-oculorgram, and electromyography data acquisition. Sixteen-bit sigma-delta analog-to-digital converters simultaneously acquire up to 12 channels of near medical quality data, even in environments with high levels of electromagnetic interference.

The EEG module acquires data at a rate of 240 sps, but data rates of up to 1,000 sps are possible. Aliasing of out-of-bandwidth signals is less than −80 dB between 1 Hz and 50 Hz. To conserve power the microprocessor operates in a low-power "sleep" mode when not acquiring data, and the run time when acquiring eight channels of EEG data is in excess of 80 hours from two AAA batteries.

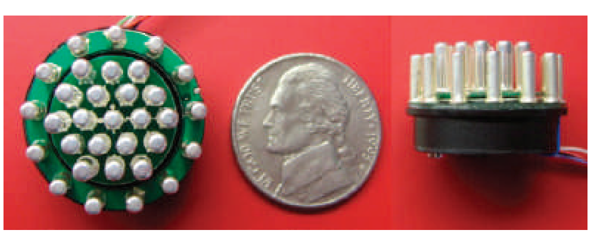

Figure 2. Hybrid electroencephalogram biosensor (with a U.S. 5 cent coin for scale).

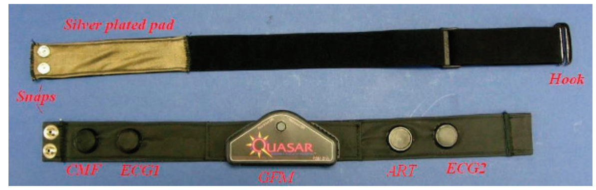

Figure 3. Physiological status monitor belt.

The short range wireless transceiver in the DAQ forms a Personal Area Network with a custom Base Station that is worn on the subject's hip or carried in a backpack, logs data to a FLASH card for storage, and communicates with external systems via proprietary, 802.11 or Bluetooth wireless protocols, Ethernet, USB 1.1 or 2.0, or RS-232.

To conserve power, the wireless transceiver transmits information in a data "burst" mode, and data rates up to 2.5 ksps have been achieved.

Measurements

Validation testing has been performed on two subjects at a Future Combat Systems technology demonstration (at the Boeing facility in Huntington Beach, California); on four subjects at a Honeywell facility in Minneapolis, during a NATICK data gathering exercise; and on two solders performing combat tasks in a realistic training environment at the Aberdeen Test Center in Maryland. Classification accuracy of cognitive workload from subjects at Aberdeen reached 90 percent or higher for both participants. The data presented in this article were obtained during extensive testing under simulated operational conditions at Quantum Applied Science and Research. In all of the measurements no preparation of the scalp was performed at the hybrid electrode sites. Preparation of the scalp for the wet electrodes included abrasion with Nu-Prep, followed by cleaning with alcohol and then application of Grass EC2 electrode paste.

Figure 4. Hybrid sensor array incorporated into a soldier's Kevlar helmet. Left: The outer aluminum ring and weights load the harness correctly when the helmet is not present. Right: Electroencephalogram system with helmet attached and ready for use, including wireless module.

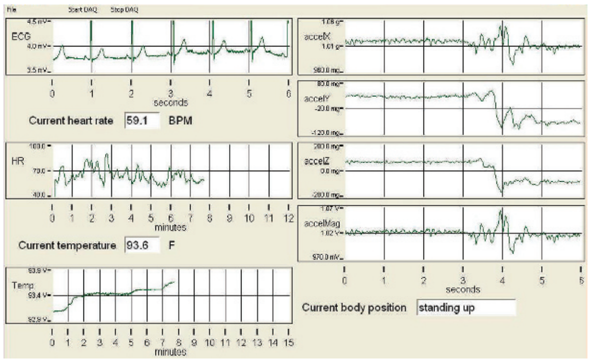

Figure 5. Screenshot showing electrocardiogram and accelerometer data collection using the physiological status monitor.

Physiological data recorded by PSM

A screen capture of physiological data (ECG, temperature, and acceleration) from a subject wearing the PSM is shown in *Figure 5*. ECG data acquired in real time is converted to heart rate, where the accelerometer data are used to correct for motion artifacts.

Equivalence of EEG signals detected by hybrid electrodes and conventional wet electrodes

Simultaneous measurements were made using hybrid/wet electrode pairs positioned at the nominal CZ and FZ positions. Less than 5 mm separated the hybrid and wet electrodes placed at each position.

In *Figure 6* hybrid and wet electrode data are overlaid to illustrate the similarity in the signals measured. Alpha activity is observed in all electrodes, and the correlation between hybrid and wet electrodes is in excess of 90 percent at both electrode sites.

EEG measurement during subject motion

Figure 7 compares EEG data recorded with a subject sitting (upper trace) and with a subject walking on a treadmill at 2 mph (lower trace), measured with the wireless EEG system. The signal level in both traces indicates no significant increase in artifact during subject motion.

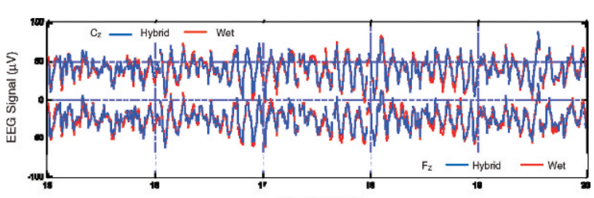

Figure 6. Comparison of electroencephalogram data (eyes closed) recorded using hybrid and wet electrodes. The data are high pass filtered at 1 Hz and low pass filtered at 30 Hz with 8th-order Bessel filters.

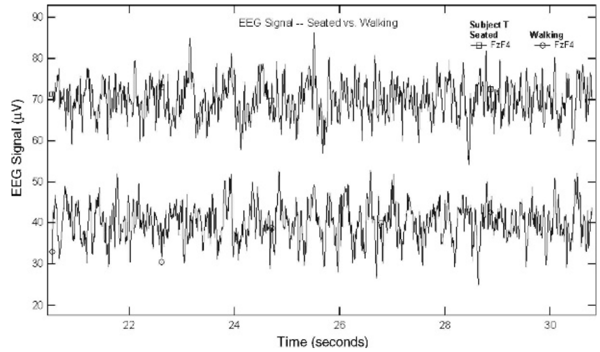

Figure 7. Representative difference data for the FZF4 electrode sites when the subject is sitting (upper trace) or walking on a treadmill at 2 mph (lower trace). The data are high pass filtered at 1 Hz and low pass filtered at 30 Hz with 7th-order Bessel filters.

Real time classification of workload

Figure 8 shows the result for real time classification for a subject walking at 2 mph on a treadmill and performing N0 (low) and N3 (high) workload tasks. Two trial data sets were first collected to train a workload classifier: a passive trial, during which the subject listened to music, and a trial in which the subject performed a divide-by-seven task. The classification results in *Figure 8* were derived using classifiers constructed from training data sets collected 19 days earlier. The vertical axis is the probability that the subject is undergoing a high workload task. The N0 task shows a low probability (always less than 30 percent); the N3 task shows a significantly higher probability, reaching 100 percent on numerous occasions.

Figure 9 shows the EEG system being used for real time classification of cognitive workload and engagement while subjects play a first-person shooter video game. Classifiers were constructed for each subject using three training data sets: data collected during passive viewing of the game, while fighting two

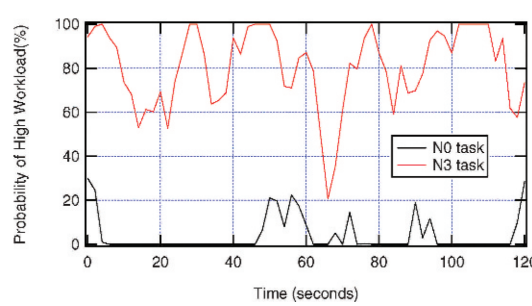

Figure 8. Real time classification while subject was walking at 2 mph on a treadmill and performing an N0 task and an N3 task. Two trial data sets were collected to train the classifier at different workload levels: a passive trial, during which the subject listened to music, and a trial in which the subject performed a divide-by-seven task.

Figure 9. A test system for assessing workload and engagement of computer gamers.

enemies in the game, and while fighting 25 enemies in the game. The classifiers for a given subject were then used to perform real time classification of workload while the subject was playing the game.

A screen capture for the subject engaging 25 enemies is shown in *Figure 10*. The workload indicator on the right of the screen is a real time estimation of the cognitive state of the subject and is a combination of two separate classifiers: a Workload classifier (High/Low) and an Engagement classifier (Engaged/Disengaged). The subject's workload level in *Figure 10* (High) is an accurate reflection of the workload at this level of difficulty in the video game.

Table 1 presents the classification accuracies for each classifier for a series of tests conducted on 4 separate days (over a period of 10 days). Intrasession cross validation for each day was performed using 60 percent of the data for training and 40 percent for classification and repeating this process eight times. Real time classification accuracies are also presented for data in which the training data sets are from one day and classification was performed during testing on a subsequent day. The 4 days of testing have been paired as shown in *Table 1* because the protocol was altered to

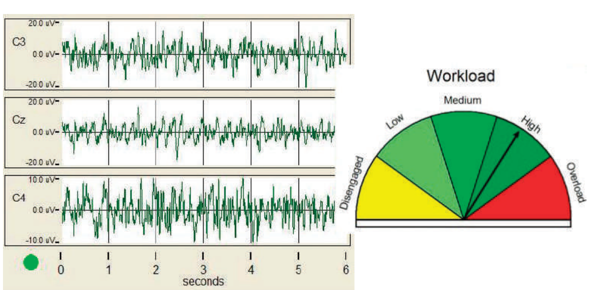

Figure 10. Laptop screenshot showing data collection and engagement classifier running on the gaming subject of Figure 5. The traces on the left are electroencephalogram signals at C3, CZ, and C4 respectively. The Workload indicator shows the real time output of the classifier.

Table 1. Classification accuracy

Training data set/ classification data set	Workload classifier (%)	Engagement classifier (%)
Cross validation, March 28	83.6	89.1
Cross validation, April 1	86.1	88.2
Cross validation, April 5	83.4	84.9
Cross validation, April 6	73.8	84.3
March 28/April 1	81.4	81.1
April 5/April 6	74.8	78.8

32 enemies for April 5 and April 6 because of an increased proficiency of the subject at playing the video game.

The results in *Table 1* demonstrate that the Workload and Engagement classifiers routinely achieve greater than 80 percent classification with 8 seconds of temporal smoothing. Similar classification accuracies are also found when the training data sets are taken from a different day, demonstrating the classifiers' robustness to daily variations in physiological state.

Final remarks

Quantum Applied Science and Research has developed an integrated system for measuring warfighter physiology. The wireless EEG system is compact, lightweight, and ultralow powered. Using innovative noninvasive bioelectric sensors that operate through hair without skin preparation or conductive gels, EEG data of quality similar to that of conventional wet electrodes can be obtained. The noninvasive nature of the EEG system (i.e., zero skin preparation, minimal wiring) permits greater subject freedom of motion and considerably improves user compliance for such systems. Hardware has been integrated with robust proprietary classifiers that enable real time determination of cognitive workload, engagement, and fatigue. Mechanical isolation built into the harness permits the recording of high quality EEG data even during subject motion.

Military applications of the PSS include monitoring of physiological states for Dismounted Infantrymen, or cognitive state monitoring for Command & Control personnel. Applications of the EEG system extend beyond cognitive state determination to medical applications, such as the monitoring of patients with epilepsy or other neurological conditions, and to computer interfaces for the disabled. ❑

Dr. R. Matthews is the leader of QUASAR's Biosensor Development Program. He leads the development of bio and medical applications and has been responsible for all

clinical trials and technology demonstrations of biosensing devices. Dr. Matthews has extensive, in-depth experience in developing a broad range of practical EM sensing systems for airborne, land, underwater, and man-carried operations. These projects include being the lead designer and engineer on a series of research programs culminating in a total of more than $30 million in R&D funds to build a land mine detection system. While working for Quantum Magnetics (QM), Dr. Matthews was stationed at the IBM Thomas J. Watson Research Center, where he worked closely with IBM on the development and commercialization of advanced magnetic technologies. This work formed a key part of the superconducting technology development agreement between IBM and QM. Dr. Matthews led the development of instrumentation using high-temperature superconducting magnetic sensors for biomagnetic measurements. He also played a key role in the development of a multisensor magnetic gradiometer and contributed to work using magnetoresistive sensors for buried explosive detection. Before coming to the United States, Dr. Matthews worked on the development of a superconducting gravity gradiometer, a geophysical exploration device to be flown in light aircraft to survey for massive ore bodies. This work was aimed at commercializing the sensor for the geophysical exploration market. Dr. Matthews is author or coauthor on many scientific publications and is the inventor or co-inventor on numerous patents. Dr. Matthews earned his Ph.D. in Physics from The University of Western Australia. E-mail: Inquiries@quasarusa.com

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The Dirty, the Boring, and the Dangerous: Uninhabited Aerial Vehicles—An Engineer's Perspective

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It is easy to be attracted to a new technology. We think, "it's so cool, and look at what it can do!" We are so enamored that we do not see the limitations or the full possibilities, either positive or negative. We only see the shiny new toy that is the technology. We want to apply it everywhere we can. We embody the old adage, "if you're a hammer, every problem looks like a nail."

The problem is that we are so attracted to the technology that we overlook the underlying potential. Look at Digital Fly-By-Wire (DFBW). What a powerful idea! Pursued at the NASA Dryden Flight Research Center from 1970 to 1985, DFBW at first enabled pilots to achieve greater stability, not by traditional mechanical linkages to flight control surfaces, but through computers and electrical circuits. NASA research pilot Gary Krier made the first Phase I flight with DFBW on May 25, 1972, aboard a modified Navy F-8U Crusader. After Phase I ended in 1973, the Phase II Shuttle program (adapting DFBW to the Space Shuttle) lasted from 1976 to 1978. Soon, planes as diverse as the F-16 and F-18, the Airbus A 320, and the Boeing 777, among others, flew with DFBW to enhance controllability and flying qualities.

Quickly, however, it dawned on researchers that DFBW technology could serve the opposite purpose for which it was first intended: not to enhance static *stability*, but to stabilize systems that had *no* inherent static stability at all. Experiments were made on several full-scale, statically unstable aircraft and even on a few production aircraft. Only 10 years later did we realize that the real advantage of DFBW lay in the ability to use digital algorithms to create advanced control algorithms, to use modern control theory algorithms, and to linearize systems that had massive inherent nonlinearities, or even adaptive control algorithms.

The case for uninhabited aerial vehicles (UAVs)

This failure to see the obvious in a new technology likewise applies to UAVs, also known as Uninhabited Autonomous Systems. These aircraft, controlled by a pilot from a cockpit removed from the actual aircraft (usually on the ground, but not necessarily so), have a long precedent at NASA. Starting in 1969, researchers at NASA Dryden flew the Hyper III project, a remotely controlled subscale lifting body aircraft. During the early 1970s, Dryden engineers investigated high angle of attack departure and recovery techniques on a subscale F-15 spin research vehicle. At about the same time, NASA also embarked on the Highly Maneuverable Aircraft Technology Program, in which two remotely piloted research vehicles, built to 44 percent scale, were flown by pilots from a ground station. (The Highly Maneuverable Aircraft Technology project managers felt the flight program was too hazardous for humans to be in the cockpit.) The two Highly Maneuverable Aircraft Technology demonstrators flew at Dryden from 1979 to 1983.

Concerns about the earth's atmosphere and the desire to perfect low-cost earth sensing prompted NASA in 1990 to begin a program of high altitude, long duration aircraft platforms that came to be known as the Environmental Research and Sensor Technology vehicles. During 10 years of flight research, the Environmental Research and Sensor Technology program won a place in world aviation history in August 2001 when the Helios Prototype achieved an altitude of 98,863 miles, more than 2 miles higher than the previous record for sustained level flight by an aircraft.

There have been other crucial UAV achievements since this milestone. The most recent advances have been in the use of the Ikhana ("intelligence" in the Native American Choctaw language), a civilianized version of the military's MQ-9B Predator B aircraft. Its remote sensing capabilities enabled NASA to collaborate with the U.S. Forest Service to fight forest fires (more about this later) and with the U.S. Wildlife Service to do fisheries surveillance.

As a result of all of these projects, some have envisioned radical uses for future UAVs, including airliners with no pilots on board, autonomous systems that can carry cargo, or perhaps UAVs that replace satellites for communications. The reality is that none of these applications appear to have near-term potential. Of course, the high-altitude long-endurance mission is an obvious application, but it will require additional technology development, mostly because it is quite unlike the aircraft concept and much more analogous to a spacecraft. The high-altitude long-endurance missions will require infrequent maintenance, long duration reliability, and the ability to operate in the rarefied upper atmosphere, which is not well understood and rather hostile. In this one respect at least, the aircraft/UAV community should start thinking more like the spacecraft/satellite community, especially in regard to periodic maintenance.

But at the same time, UAVs still represent the classical problems of pilot-vehicle interface, as well as handling qualities and flying qualities, although they are very different in this class of vehicle compared to traditional aircraft. How are these essentials of flight control translated into UAV practice? What is the function of one-click or two? Does right-click do something harmful to the system? What about lost-link? Do we have graceful degradation with contingency management? Instead of commanding roll-rate, should we command bank angle? Should we command pitch angle rather than pitch-rate or angle-of-attack? Do we have issues with pilot-induced oscillations or over-control (especially with intermittent link via satellite and inherent time-delays)? What is the role of autonomy versus the role of the pilot in this system?

Like other new technologies, UAVs have some uses that are so superior to traditional approaches that it is amazing that no one recognized them right away. The best three are obvious: they should be used for missions that are *too dirty, too boring, or too dangerous for pilots.*

None of these three missions conflicts with the realm of the pilot flying in the cockpit. It takes a lot of training and dedication to become a pilot, and pilots enjoy an elite status in the aeronautics community—deservedly so. It should not surprise us if they bridle at the thought of being replaced by automation. Brian Muirhead—the brilliant engineer who gave us Sojourner, the six-wheeled vehicle that traversed Mars during the Pathfinder Mission—once said that all the months of exploration on Mars by all the unmanned missions that successfully landed on its surface could have been replaced easily with a few hours of human exploration. This is not to say that autonomous robotic missions should be replaced by fewer, and far more costly, manned missions. But there is an appropriate technology for every mission. In many instances, the adaptations at which we humans are so good surpass our ability to impart such adaptations to machines (although the gap is closing and such advances may be on the horizon).

The dirty

We all watched in disbelief—over and over again on national television—as the World Trade Center in New York City came crashing down on September 11, 2001. We were horrified and transfixed. The south tower collapsed first at 9:59 AM upon impact with United Airlines Flight 175; the north tower went down at 10:28 AM after being struck by American Airlines Flight 11. These massive structures, each containing 13.4 million feet of office space, together constituted 14 percent of the office inventory in Manhattan. As the stew of superheated steel, plastic, paper, and other vaporized ingredients sent clouds of white dust over and through the Manhattan skyline, our immediate response was to help the victims.

Of course, the first rule in search and rescue is to not become a victim yourself. Yet no one knew what was in that dust (Prezant 2008). Was it filled with asbestos? Did it contain a carcinogenic ash by-product from the fires? Was the ash toxic? Were there some other, unknown contaminants?

What would we have given to know what was in those clouds? We might have known had we dispatched a small UAV—like a radio-controlled airplane—piloted from a safe distance, just out of reach of the ash cloud, to sample its composition. As it penetrated the ash, we would have learned what real hazards New York's brave men and women faced as they worked to save lives.

Other applications can be imagined. Volcanologists could use UAVs to gather gas samples, and many other scientists working in threatening environments could mobilize UAVs to collect data.

The boring

Many missions require extremely long duration with lots of time in a loitering mode, for example, those associated with fighting forest fires. Having real-time data on fire "hot spots" and the progress and direction of the fire front can have a huge effect on how ground crews are deployed to combat fires.

Imagine a long endurance UAV (perhaps like an extreme endurance version of the MQ-9B Predator) loitering over a fire. The aircraft stays aloft for 2 days, and can spend 44 of those hours on-station, watching events and reporting data to hardworking crews battling the blazes.

Of course, the pilots of such aircraft operate far away from the fires themselves. Safely housed in mobile facilities miles away, they take shifts to give 24-hour coverage, and replan their missions so they can observe each hot zone the moment it crops up. NASA has already experimented with such a "fire pod" and the technology shows great promise (NASA 2008).

Indeed, this mission is more than speculative. During late October 2006, as wildfires engulfed much of Southern California, a NASA Altair UAV roved over the devastating Esperanza Fire, which took the lives of five firefighters. Via satellite, it sent more than 100 real-time images pinpointing the behavior of the blazes. In late October 2007, NASA dispatched the Ikhana aircraft—equipped with the Autonomous Modular Scanner, developed at NASA Ames—over two gigantic infernos in the San Bernardino National Forest, one at Camp Pendleton Marine Corps Base, four in San Diego County, and one in Orange County's Cleveland National Forest.

The dangerous

During the late 1990s, satellites collected the first data indicating that human activities were having an adverse effect on the planet's atmosphere. The satellite data warned of ozone depletion, most probably due to chlorofluorocarbons (CFCs) in the upper atmosphere (60,000 to 70,000 feet msl) (U.S. Environmental Protection Agency 2008). Ozone is instrumental in protecting the biosphere from ultraviolet radiation from the sun. Among its ill-effects, ozone depletion has been projected to increase the rate of skin cancer in humans by two percent for each one percent of ozone lost in the atmosphere (De Gruijl 2004).

This phenomenon was observed using remote sensing satellites in the polar-vortex during the long, dark polar night. However, no hard, in situ data existed to support the remotely sensed satellite data. Because the Environmental Protection Agency and the National Oceanographic and Atmospheric Administration scientists and engineers lacked the resources to make such direct measurements, they asked NASA to make flights to acquire this additional information. Once ozone depletion was directly linked to CFCs being trapped in the upper atmosphere, the industrialized world reacted quickly. The polystyrenes that carried the CFCs, which were released into the air as they degraded, were banned and reformulated to eliminate the CFCs. The ozone depletion has been reduced, and the ozone hole is now shrinking.

For this research, NASA used a well-proven aircraft, the Earth Resources-2, a civilian version of the famed U-2 high-altitude reconnaissance aircraft. However, for this mission, the Resources-2 has one glaring fault: it had only one engine.

Why should this fact matter? Ozone depletion seems to occur in the polar winter, when the sun does not rise for months. In these conditions, daytime highs might reach –40 degrees.[1] Should an engine emergency occur in this extreme climate because of fuel feed failure, foreign object damage, flameout, or other factors, the pilot has almost no chance of survival. Indeed, NASA requires a waiver of normal procedure in order to authorize such flights because of the extraordinary risk to life.

However, if the Global Hawk RQ-4A aircraft had existed in the 1990s, there is not much doubt that the mission would have been performed with a UAV rather than a piloted aircraft. The ozone case represents one of many other instances in which the threat to human life can be dramatically reduced with appropriate use of UAVs.

The UAV future

The twenty-first century offers vast opportunities for UAV technologies. We are only at the leading edge of what might be possible. But we should be careful to use this technology in an appropriate manner. There is an important lesson to be learned from the past. When early UAV systems were first proposed, we spent our precious resources developing new platforms on which to try out the automation algorithms. If the objective is to develop a new capability, it makes perfect sense to build a new airframe. But if the point is *automation*, why expend limited research budgets on new airframes? Why not apply the automation to existing airframes—why not an F-16 UAV system, for example? Perhaps an augmentation of existing systems is the best approach at this juncture to maximize UAV applications.

Finally, in order to be credible among the individuals who fund research, technologists must guard against overselling capabilities. A careful and measured approach using technology appropriate for the mission, and carefully husbanding our resources for the greatest benefit, should inform all of our choices. ❑

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20 years and later the chief of aerodynamics. His major areas of research included low Reynolds number airfoil development in both flight research and computational method validation, aerospace vehicle flight mechanics, aerodynamic and thrust vectoring interaction, boundary-layer development research at high-subsonic conditions, reentry vehicle aerodynamics, subsonic and hypersonic aerodynamics and stability and control of single stage to orbit and reentry vehicles, helicopter performance research, high angle of attack aerodynamics of high performance jet aircraft research, aerodynamic parameter estimation of hypersonic flight data, aerodynamic and thrust vectoring parameter estimation from flight data, and induced drag minimization coupled with flight mechanics and structural optimization. He has been selected for several significant awards, including the NASA Exceptional Service Medal and multiple honors for mentoring and technical leadership. He is the technical chair of the Western Workshop of the Experimental Soaring Association arm of the Soaring Society of America and is a member of the United States Hang Glider Association. Mr. Bowers has served as the Chief Engineer for seven major aircraft projects at Dryden (the SR-71A Aerodynamic Experiments, the F-18 High Angle-of-Attack Research Vehicle, the F-106 Eclipse Aero-Tow, the X-48A Blended Wing-Body Low Speed Vehicle, the X-38 Boost Launched Aerodynamic System Test, the X-37A Approach and Landing Test, and the AIAA/NASA Wright Flyer Instrumentation project) and as Principal Investigator for five major experiments (X-30A National Aero Space Plane aerodynamic model, the F-18 High Angle-of-Attack Research Vehicle Aerodynamic and Thrust Vectoring Interaction Model, the F-18 High Angle-of-Attack Research Vehicle Thrust Vectoring Model, the APEX high altitude aerodynamic airfoil experiment, and the In-Flight Schlieren Flow Visualization System for Sonic Boom research. Email: Albion.H.Bowers@nasa.gov

Endnotes

[1]At −40 the designations Celsius and Fahrenheit are unnecessary—the temperature is the same.

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ITEA Journal 2009; 30: 23–28

The Air Force Agency for Modeling and Simulation: Advancing Modeling and Simulation for the Warfighter

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In the mid 1990s General Ronald Fogleman, then U.S. Air Force (USAF) Chief of Staff, was determined to correct the deficiencies in modeling and simulation (M&S) that were uncovered in the months and years following Desert Storm. The existing models, technology, and expertise did not accurately represent air and space power, particularly in Joint exercises, experiments, and studies. This was exacerbated in that the Combatant Commanders did not have accurate air and space power representations when formulating contingency plans, nor the ability to accurately rehearse those plans with the limited airpower simulations that would drive their exercises. Additionally, the Air Force was not yet exploiting the power of simulation to properly communicate to Congress and the Office of the Secretary of Defense on such issues as roles, missions, and funding. An M&S policy office was established but still had no governance structure. The Air Force had no top-level Air Force integrator or servicewide coordinating processes and integrating initiatives, and had many competing air models.

As a result, General Ronald Fogleman signed "A New Vector" in 1995 *(Figure 1)*, outlining the USAF's plan to improve its use of M&S. At a four-star Summit, the Chief of Staff of the Air Force (CSAF) and the Secretary of the Air Force (SAF) sponsored the creation of an Air Staff Field Operating Agency (FOA) in Orlando, Florida, to specifically meet these challenges, the Air Force Agency for Modeling and Simulation (AFAMS). Headquarters USAF Program Action Directive 96-4 officially implemented the CSAF's decision and AFAMS stood up on June 3, 1996.

Today, AFAMS, which is aligned under the Secretary of the Air Force, Office of Warfighting Integration and Chief Information Officer (SAF/XC), is commanded by Colonel James Dennis. Col Dennis leads a diverse organization that oversees M&S activities around the globe and maintains liaison officers at Nellis and Hurlburt Air Force bases. AFAMS is strategically located in Orlando, Florida, because of the synergy created by the presence of all of the Services: Army Program Executive Office—Simulation, Training, Instrumentation; Naval Air Warfare Center Training Systems Division; and Marine Corps Program Manager Training Systems. The Services' primary simulation and training acquisition and sustainment organizations comprises over 2500 people and $5 billion a year in business, and are colocated in the Central Florida Research Park adjacent to the nation's sixth largest university, the University of Central Florida.

AFAMS' mission is to ensure appropriate representation of air, space, and cyberspace in modeling and simulation; integrate and ensure interoperability of Air Force models and simulations; coordinate Air Force M&S support for Service, Joint, Inter-Agency and Coalition events, and develop and maintain appropriate M&S skills and knowledge for Air Force personnel. AFAMS provides oversight and is the Executive Agent for a suite of simulations known as the Air, Space, and Cyber Constructive Environment (ASCCE). These simulations are the authoritative representation of air, space, and cyber power for U.S. Title 10 training exercises and mission rehearsals conducted jointly in all major commands around the world *(Figure 2)*. The Electronic Systems Center at Hanscom Air Force Base (AFB) is the program office overseeing development of

Figure 1. General Ronald Fogleman articulated his vision for M&S in 1995.

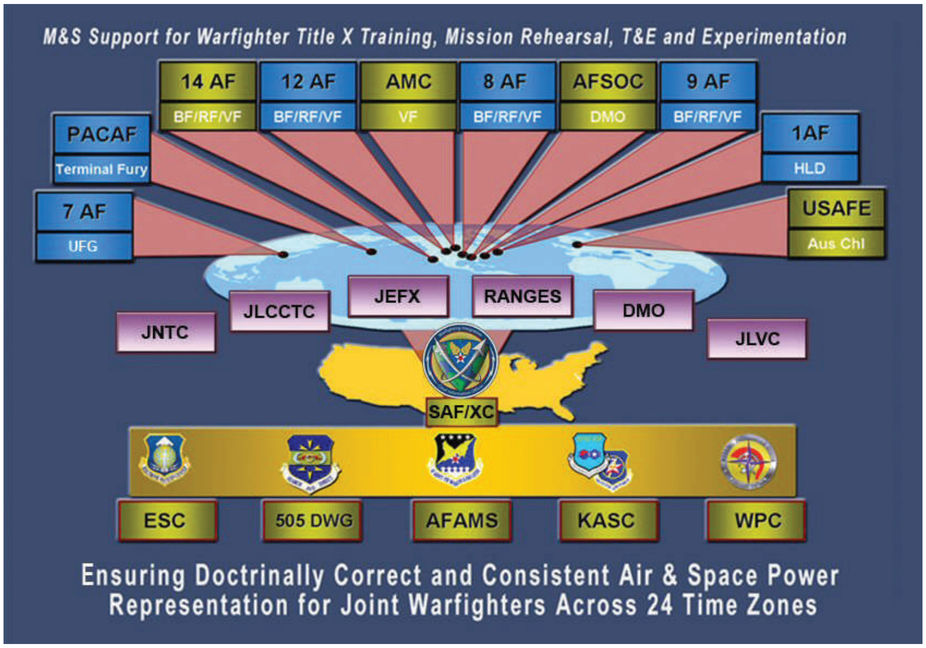

Figure 2. ASCCE is used throughout the USAF for warfighter events. It is the authoritative air, space, and cyber representation for certifying Joint Force Air Component Commanders and their staff.

the simulations. The 505th Distributed Warfare Group at Kirtland AFB, the Korean Air Simulation Center at Osan Air Base, the Warrior Preparation Center in Germany, and the 1st Air Force at Tyndall AFB are the organizations and major simulation centers conducting Title 10 training and other exercises where ASCCE is leveraged. AFAMS provides M&S expertise and the simulations for such venues as Pacific Command's Terminal Fury, European Command's Austere Challenge, and U.S. Forces Korea's Ulchi Freedom Guardian. ASCCE stimulates real world systems for Air Operations Centers and provides air power; intelligence, surveillance, and reconnaissance virtual imagery; and integration. ASCCE provides the ability to interface and stimulate operational command and control systems, broadcast systems, and can interface to virtual and live-fly systems to provide for integration in a Live, Virtual, and Constructive (LVC) environment.

AFAMS works with the Air Force, the other services, and Joint Forces Command on a broad range of activities where M&S is required to represent air and space power. AFAMS also provides oversight and subject matter expertise of the ASCCE for use in experimentation and demonstration events such as the Joint Expeditionary Force Experiment (JEFX) and the Coalition Warrior Interoperability Demonstration (CWID). JEFX is conducted by another FOA under SAF/XC, the Global Cyber Integration Center. JEFX consists of experiments with participation from sister services, coalition nations, combatant commands, and government agencies to assess initiatives to fulfill identified gaps in warfighting capability. CWID is the Chairman of the Joint Chiefs of Staff's annual event, enabling combatant commanders and our coalition partners to investigate command, control, communications, computers, intelligence, surveillance, and reconnaissance solutions for enhancing coalition interoperability. CWID investigates information technologies that have the potential to integrate into an operational environment within the near term following demonstration execution every year in June.

In the early 2000s, AFAMS, along with Air Combat Command and the Air Staff and several other organizations, led an initiative to increase the distributed simulation capabilities across the Air Force and achieve the CSAF's vision for Distributed Mission Operations (DMO). An Initial Requirements Document and a Concept of Operations were approved by the Air Force Requirements Oversight Council and the CSAF to promote the concept of using distributed virtual fighters, bombers, and intelligence-surveillance-reconnaissance platforms with constructive simulations supporting battlestaff (up to the Combined Air Operations Center) in a small team and larger total team environment. Bridging the tactical to operational levels of war, DMO has grown to include more players at more locations around the world. AFAMS leads the DMO Technical Management Working Group to address the overarching technical challenges and issues with bringing such a diverse group together for training events.

AFAMS continues to provide capabilities to the field in ever-expanding arenas. One such area has been developing the architecture to support the USAF Warfare Center's (USAFWC) training of the Air Support Operations Center Initial Qualification Course. Complementary to this, AFAMS is providing the architecture expertise and simulations for the Joint Terminal Attack Controller on the live ranges that the USAFWC integrates with during joint training events. AFAMS is working with Red Flag at Nellis, a multinational exercise providing a realistic environment to practice combat scenarios, to support the live fly with computer simulations in a variety of means (intelligence-surveillance-reconnaissance, command and control, threats). These and similar activities are part of a broad effort to integrate "live-fly" participants with participants in virtual simulators and constructive simulations representing computer generated forces (collectively termed LVC) into a seamless environment that can be used for training, testing, experimentation, analysis, and similar functions.

5-year plan for an LVC Constructive Integrating Architecture

The Army has established a Joint Requirements Oversight Council (JROC)–approved LVC Integrating Architecture (LVC-IA) program to help manage Army progress in using LVC capabilities for training. Building in part on the Army's success, an Air Force LVC-IA program is being initiated to establish a coordinated, programmatic approach to achieving persistent, integrated LVC capabilities.

The key precepts to accomplishing this objective are: (a) *Do no harm* (don't break what works). (b) *Interoperability is not free* (focused investment is required). (c) *Start with small, immediate steps* (work fifth generation training shortfalls and other critical challenges first). (d) *Provide centralized management* (provide a corporate Air Force perspective and cross-functional standards and solutions). The fundamental approach and focus of the LVC-IA is to establish an LVC Enterprise perspective to all LVC efforts, and forge commonality, consistency, and efficiency through an integrating architecture. The Air Force is developing an LVC-IA 5-Year Plan to guide the major commands and the acquisition product centers on a clear path to success.

The LVC-IA Program will have multiple areas of technical and nontechnical challenges to work on behalf of all user communities. The guidelines for the LVC-IA 5-Year Plan and for an initial implementation plan are in coordination across the Air Force in a draft document worked on throughout 2008. AFAMS hosted two government-only meetings in June and September 2008 and briefed the M&S General Officer Steering Group in November 2008 on the way ahead to achieving an LVC-IA.

Why a USAF Enterprise LVC-IA?

The Air Force has Integrated LVC simulation capabilities in select areas within the Air Force training community. Blue Flag exercises have used virtual environments to enhance their training objectives. Virtual Flag exercises have merged multiple virtual simulators with constructive simulations and select live systems for training and mission rehearsal. Red Flag has provided venues for large scale exercises such as Joint Red Flag to prove the value of LVC simulation primarily for training and mission rehearsal events. Unfortunately, an LVC environment must be created for each exercise, with its own tools, network services, and simulations, with no guarantee of persistent on-demand capabilities. These environments take months to plan, build, integrate, test, and then finally use for the event. They disappear after the exercise with little reuse the next time the event is staged. Senior leadership recognizes this, and at the April 2008 CORONA conference, it was noted that the DMO Program of Record is resource limited and not funded for such a broad LVC capability.

Additionally, the Air Force test and training ranges no longer have the capability to exercise to their full capability current or future weapons, systems, and aircraft. Live range space, availability, and technical capabilities are being outpaced by warfighter systems' technology. We cannot exploit the capabilities of the fifth generation F-22 or F-35 fighters, and we cannot produce adversary support sufficient to test and train fifth generation fighters. Range restrictions, won't allow for effective test and training of emerging munitions with extended range footprints. The feasibility and cost of procuring realistic double-digit surface-to-air missiles (SAMs) or limiting factors in our capability to retool existing range simulator assets highlight the challenges in training to known adversary capabilities. Reduction in the flying hour program means fewer sorties to generate the same number of aircrew needed to fill cockpits with fully mission-capable individuals. There are a number of databases and networks used by multiple players each unable to network with the other. We need architectures and standards that will fix this to provide fifth generation training. The creative integration of virtual and constructive capabilities into live test and training ranges is the only means to replicate full scale operational capabilities and support realistic training, testing, and other functional area support. In short, live range space, availability, and technical capabilities are

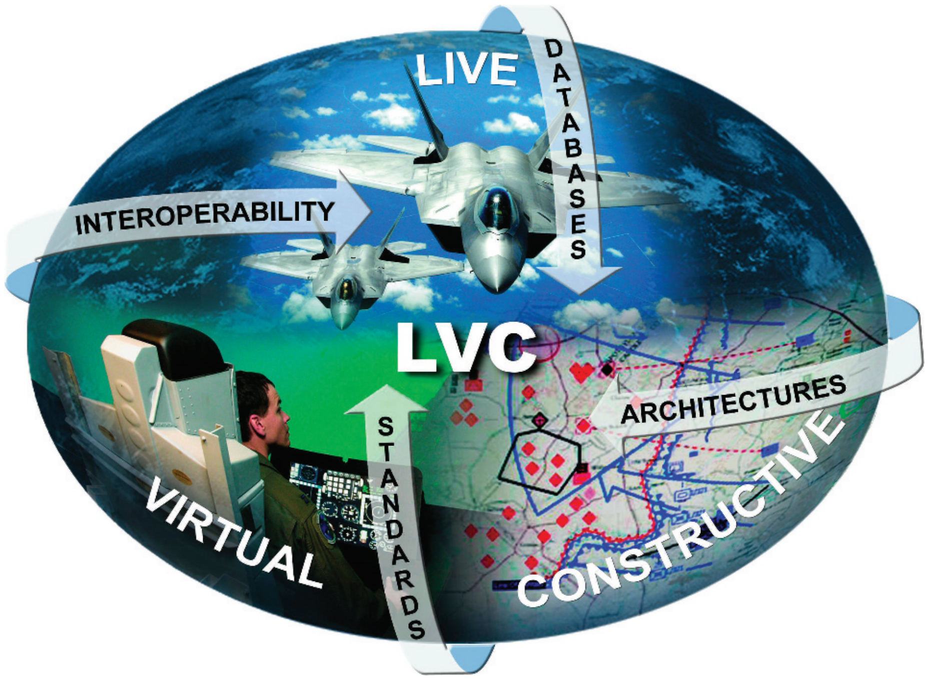

Figure 3. The LVC Integrating Architecture Enterprise Initiative will allow for more efficient federation composition and reuse in the LVC domains.

being outpaced by warfighter systems technology. This will only be exacerbated as the Air Force continues to develop technical and doctrinal capabilities to defeat emerging threats. This is a primary driver for the LVC-IA program.

A persistent LVC Enterprise will be based on enterprise standards and protocols and not just a single site's architecture, resulting in a consistent environment for development and testing *(Figure 3)*. This will help to ensure that systems acquisitions result in more inherent interoperability and simulator concurrency upon fielding. It will also help solve operational test limitations. For example, given physical range limitations, a live aircraft could fly a target engagement scenario with simulated weapons release, while a virtual-constructive environment could concurrently be used for modeling and evaluating weapon fly-out and end-game effects of the weapons.

AFAMS is working closely with the test and evaluation (T&E) community to ensure future enterprise capabilities are on track with the Office of the Secretary of Defense's *Testing in a Joint Environment Roadmap* as well as the Air Force Operational Test and Evaluation Center's (AFOTEC) *Test Capability Roadmap*. The LVC-IA will leverage the Joint Mission Environment Test Capability (JMETC), which was established in October 2006 to address the shortfalls in T&E with joint operational context. This will also serve to keep the Air Force aligned with the new Department of Defense Instruction 5000.02, "Operation of the Defense Acquisition System," dated December 2, 2008, which states in part:

> *"The PM, in concert with the user and the T&E community, shall coordinate DT&E, OT&E, LFT&E, family-of-systems interoperability testing, information assurance testing, and modeling and simulation (M&S) activities, into an efficient continuum, closely integrated with requirements definition and systems design and development." [DoDI 5000.02, December 2, 2008]*

Access to real-world architectures, weapon systems (including operational flight programs), and opposition force conditions during interoperability testing will be enhanced by leveraging the advances the training community makes along with the test communities' continued development of current and future systems.

While all functional communities are included within the 5-year plan, training will be the primary initial focus for LVC integration because of the urgent shortfall in training capabilities for fifth generation fighters and weapon systems, and ongoing global war on terror operational needs. Because of the interrelationship of testing and training, commensurate needs of the testing community will necessarily be addressed, with a parallel focus on working the breadth of test integration issues. The training and education needs of our workforce cannot be overlooked because they affect the current and emerging capabilities of our warfighters. Finally, as the plan is developed, the phased implementation of an integrated LVC architecture must be adaptable to rapidly assimilate new tactics, techniques, procedures, and technologies.

The integrated infrastructure for conducting LVC activities must be robust and responsive. The current planning and setup times are too lengthy to be responsive to rapid demands, especially in a wartime environment. A sudden Air Expeditionary Task Force deployment requires the ability to provide a mission rehearsal capability to the warfighter in *days* versus *months*. This realization means the warfighter must perform rapid planning and rehearsal using a persistent LVC environment that is relevant to the expected employment area. Further, rapid development and fielding of a critical warfighting system, such as a new weapon system, requires ready access to LVC capabilities that represent Command and Control, Intelligence, Surveillance and Reconnaissance, weapons, platforms, sensors, synthetic forces, and threats. For this LVC vision to come to fruition, an effective LVC-IA must describe a set of protocols, specifications, standards, and software that support the implementation and operation of a seamless and integrated environment.

Areas of emphasis

The LVC-IA 5-year plan is in reality a series of plans. These plans lay out measurable goals and milestones for the designated periods. Each annex represents a 5-year period, with objectives and milestones to achieve measurable progress in this multifaceted LVC-IA program. Annexes will be added over time to cover subsequent periods. The long range goal and the objective of these incremental steps is a persistent, adaptable, sustainable, and fully integrated LVC Enterprise Architecture that meets the needs of all M&S functional areas.

Workforce management

An integrated LVC Enterprise Architecture must address personnel resources as well as technical resources. Through workforce management, the Air Force will identify, educate, professionally develop, and track M&S expertise to support the LVC training environment. As the M&S training functional manager, the LVC-IA program will collaborate with major commands and other career field functional managers to determine the optimum makeup of the Air Force M&S future workforce and focus M&S capabilities and tools to support the warfighter. The Professional Development Program will provide continuing education, assist supervisors in creation of an individual development plan, and provide a community of practice with relevant information for all levels of the M&S workforce.

Policy alignment

Policies for integration and interoperability, from headquarters Air Force down to simulation centers, need to be reviewed to ensure clear and consistent guidance on implementation of M&S capabilities in support of all functional areas. Policies codifying responsibilities at major command level and below are inconsistent and, in some cases, nonexistent. To ensure effective integration and implementation of LVC-IA driven capabilities, the Air Force will need to align its policy. Working with SAF/XCDM, the Air Force's M&S Policy Division at the Pentagon, we are implementing and improving policy and procedures identified in current and future Air Force M&S policy directives and instructions. This will require top level oversight. An Air Force Requirements for Operational Capabilities Council (AFROCC)–approved program will facilitate this and help achieve a persistent LVC environment.

Programmatics

A fundamental precept of this LVC-IA plan is that a centralized management structure must be established. The acquisition category level and milestone start point will be determined based on estimated life cycle costs and HQ Air Force priorities. Proper documentation and coordination, in accordance with the Joint Capabilities Integration & Development System (JCIDS) process, will be required for program authority and funding approval. This includes securing AFROC and JROC approval to proceed. To comply with JCIDS requirements for establishing an LVC-IA Program Office, we are working on the 5-Year Plan to ensure that applicability and timelines are addressed for completing all relevant documentation.

Conclusion

Upon establishment of a centralized LVC-IA Program Office, with adequate funding for sustainment, the future of LVC activities will be on the road to persistent or semipersistent operation. Proliferation of unique solutions will diminish, reusable architectures will be established and managed, and built-in interoperability will emerge.

Operational art, according to Joint Publication 3-0, is:

> *"The application of creative imagination by commanders and staffs—supported by their skill, knowledge, and experience—to design strategies, campaigns, and major operations and organize and employ military forces… Operational art governs the deployment of those forces, their*

commitment to or withdrawal from battle, and the arrangement of battles and major operations to achieve operational and strategic objectives."

Testing and training must be tied to this concept first and foremost, for testing and training to any other purpose is meaningless to the warfighter (and ultimately the nation). Robust environments for tactical and operational level test and training that is pertinent to the tasks necessary to achieve the joint operating concepts of the Combatant Commanders requires a persistent LVC architecture:

1. Accurate and *readily available* operating environments relevant to anticipated current and future conflicts;
2. *Composable* friendly forces and opposition forces that represent enemy intent and capabilities;
3. *Feedback* capabilities that provide measurable data points to the warfighter for training tasks, and to the tester for developmental test and evaluation, operational test and evaluation, and live fire test and evaluation.

This architecture will achieve savings by reducing redundancies, inefficiencies, and standardizing the way we conduct testing and training. However, the true value of an integrated architecture to support these events is not simply a cost savings; rather, in most cases it is the *quality* measures that truly demonstrate the added benefit to accomplishing unit missions. Nonetheless, the value must be measured. Whether the mission is one of training, testing, experimentation, or other individual, team, or organizational tasks, appropriate data will be analyzed continually to ensure the optimum use of our limited Air Force resources. ❑

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2009 ITEA Journal *Themes*

The ITEA Publications Committee has established themes for the 2009 issues of *The ITEA Journal* and invites articles in the following areas:

Test and Evaluation of Highly Complex Systems (March issue). Complex systems embody the idea that the whole is greater than the sum of the parts – the large scale behavior cannot be predicted from knowledge of the individual constituents. Many of these systems are network enabled and must be tested in the presence of the network effects, including interactions with other networks, with services, and with applications. Service-oriented architectures are being integrated with legacy systems and sorting out behaviors and performance requires insight beyond the system under test. The human element – the cognitive domain – is an essential piece and is the place where perception, awareness, understanding, beliefs and values reside. This issue casts a broad net that our current test environment is being asked to accommodate: joint and distributed testing, chaos and complexity theory, emergent behaviors, virtual testing, modeling and simulation, cognition and autonomy, and assessing mission effectiveness from individual human, component, and system performance. ***(Manuscript deadline: December 1, 2008)***

The Future of Test Facilities (June issue). Shrinking RDT&E budgets signal a coming reduced workload for test facilities. To remain viable, commercial organizations seek to expand the use of facilities by redefining their markets, for example, aerospace wind tunnels are used for flow around cars, buildings, downhill skiers, and bobsledders. Government programs seek economies by partnering with industry and academia, overlapping developmental and operational testing, and attempting a peaceful co-existence between test and training. Opinions are sought on both sides of the test and training issue – what can and should be done and what can never be – as well as lessons learned from past efforts. Ideas are welcome on the synergy and benefits of other common use of test facilities: non-Department of Defense testing, non-traditional testing, extending the customer base, inclusion of experimentation, expanded use of commercial and academic test capabilities, and collaborating with international partners. ***(Manuscript deadline: March 1, 2009)***

Integrating Test and Evaluation (September issue). In December 2007 the Department of Defense issued new policies that represent a shift in emphasis from test to evaluation and promote an emphasis on integrated test and evaluation throughout the system life cycle in a seamless continuum. This issue addresses implementation and follows up the new policies to examine integrating contractor, developmental, operational, and live fire testing and the renewed role of developmental evaluation. The issue also examines the ethics and obligations of test and evaluation. Test and evaluation exist to serve the customer and must coach the customer to ask the right questions, must report the truth, report in a timely manner, and report assertively to ensure appropriate attention is paid. Questions arise from using data from Iraq as test data: how do we instrument systems to get data? How do commercial entities get customer data? How do non-military government organizations get data in areas for which they are responsible? The issue also asks: what are the impediments to realizing integrated test and evaluation and what are the limitations of doing so? ***(Manuscript deadline: June 1, 2009)***

Air & Space (December issue). The year 2009 marks the 40th anniversary of the first moon walk by Neil Armstrong. The first powered flight at Kitty Hawk, North Carolina occurred 106 years ago in December. Today space is more than exploration and air is more than airplanes. Earth is blanketed by countless satellites viewing, recording and communicating; the international space station is an orbiting laboratory; government and private organizations are pursuing commercial access to space. The national and international airspace is pushed to record densities at a time when unmanned air vehicle use is booming, and the Federal Aviation Administration is being asked to incorporate these unpiloted and remotely piloted flying creatures into the soup. This issue takes a retrospective look at how we arrived here, where technology is taking us, and the demands that will be placed on test and evaluation. Air and space constitute the realm of rockets, missiles, weapons, satellites, aircraft of every pedigree, transportation, intelligence, sensors, communications, hypersonics, and so much more. ***(Manuscript deadline: September 1, 2009)***

In addition: T&E articles of general interest to ITEA members and *ITEA Journal* readers are always welcome. Each Issue includes specialty features, each 2-3 pages long: **"Featured Capability"** describes unique, innovative capabilities and demonstrates how they support T&E; **"Historical Perspectives"** recall how T&E was performed in the past, or a significant test or achievement, often based on personal participation in the "old days" of T&E.; **"TechNotes"** discusses innovative technology that has potential payoff in T&E applications or could have an impact on how T&E is conducted in the future. **Interested authors**: should submit contributions to the **ITEA Publications Committee Chairman (itea@itea.org, attn.: Dr. J. Michael Barton)**. Detailed Manuscript Guidelines can be found at **www.itea.org** under the ITEA Publications tab.

ITEA Best Paper

ITEA Journal 2009; 30: 31–38

Government and Academia Partnership to Test and Evaluate Air Traffic Control Decision Support Software

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In the current air transportation system, decision support tools aid air traffic controllers in monitoring air traffic to maintain minimum separation standards between aircraft. These automated systems provide this service by predicting aircraft flight paths (trajectories) to foretell potential conflicts. The User Request Evaluation Tool (URET), developed by MITRE Corporation's Center for Advanced Aviation System Development, is an example of a decision support tool currently in operational use. The Federal Aviation Administration (FAA) has developed a new air traffic control system to replace URET. This system is called ERAM, for En Route Automation Modernization, and is being developed by the Lockheed Martin Corporation. After the Factory Acceptance Test Run for Record, a study was conducted by the Conflict Probe Assessment Team in support of the testing and evaluation of ERAM's trajectory prediction accuracy and strategic conflict probe. This article describes the partnership between the FAA and Rowan University established to develop visualization tools that aid the analysts evaluating the Run for Record test data. In addition, features of these visualization tools, how they were instituted during the study, and collaboration success stories are presented.

Key words: Aircraft trajectory; collaboration; conflict prediction; ERAM; Federal Aviation Administration; partnering; Rowan University; technology transfer; visualization.

The test and evaluation (T&E) process is the key to ensuring that a system is reliable, maintainable, and safe. It is the Federal Aviation Administration (FAA)'s mission to maintain a safe and efficient airspace system; hence the FAA is continuously exploring ways to improve their T&E abilities. The William J. Hughes Technical Center (Technical Center) in Atlantic City, New Jersey, is the lead test and evaluation facility of the FAA. The Technical Center has always valued partnerships that help improve the challenges of T&E. The Technical Center has embarked on collaborations with other international organizations through Action Plan 16 with EUROCONTROL, intergovernmental agencies through the Joint Development and Planning Office and Next Generation Air Traffic System (NextGen), industry through a Collaborative Research Development Agreement (CRDA) with the Boeing Company developing the Aircraft Intent Description Language, and academia through the FAA/NASA Joint University Program. These collaborations have been proven to be vital in enhancing the T&E process.

Introduction

The FAA has developed a new Air Traffic Control (ATC) system to replace the existing host computer system in the en route domain. This system is called ERAM, for En Route Automation Modernization, and is being developed by the Lockheed Martin Corporation (LM). One primary component of ERAM is the Decision Support Tool (DST), which assists air traffic controllers in separating air traffic. Two key functions of ERAM's DST are the prediction of the future flight paths of the aircraft and the prediction of future conflicts between two aircraft or between an aircraft and a special use airspace. The

This article was selected as the ITEA Best Paper–First Place at the Annual ITEA Symposium, November 10–13, 2008, Atlantic City, New Jersey

Factory Acceptance Test (FAT) was successfully performed by LM in September 2007. After the FAT Run for Record (RFR), a study was conducted in support of the testing and evaluation of these two key functions (Paglione et al. 2008a). This study was conducted by the Conflict Probe Assessment Team (CPAT) in the Simulation and Analysis Team (AJP-661) at the Technical Center.

To properly test ERAM, we needed a large amount of data to analyze, thus the system outputs an ample amount of air traffic data. Visualization tools create visual overviews of the large amounts of abstract data that usually are stored in various database tables or files. With the involved task of analyzing the data, a need for visualization tools with which to easily interface the data was realized. Development of visualization tools is not a skill set that CPAT possessed; therefore, CPAT partnered with Rowan University's Software Engineering, Graphics, and Visualization Research Group (SEGV). Through this collaboration SEGV developed visualization tools to aid the analysts in evaluating the ERAM RFR test data in the newly established FAA/Rowan Air Transportation Research Laboratory (FRATR Lab). The FRATR Lab, located in the Department of Computer Science at Rowan University, is where SEGV was tasked to develop the visualization tools. The partnership proved to be a successful formula in achieving the goals of testing ERAM. Furthermore, using Rowan University was essential during this study because it allowed the analysts to focus primarily on data analysis and generation of test and evaluation reports, thus expediting the analysis and lessening the workload.

This article details the tools and how they were used in the testing and evaluation of ERAM, and the background of how the partnership between the FAA and Rowan University was established, its history, and its successes. Furthermore, we present descriptive illustrations of the visualization tools and application examples of their use.

ERAM trajectory and conflict prediction accuracy study

In 1996, the FAA established the CPAT at the Technical Center to evaluate the accuracy of the conflict probes in DSTs. Since its creation CPAT has measured the conflict prediction accuracy of URET (Cale et al. 1999), and measured the trajectory modeling accuracy of both URET and CTAS (Cale et al. 1999; Paglione et al. 1999). In 2004, the ERAM Test Group formed the Automatic Metrics Test Working Group. The group, led by CPAT, established a set of metrics to measure the performance of key functions of ERAM during developmental and operational testing (Paglione et al. 2006b). In 2007, ERAM was accepted by the FAA, having passed the performance requirements during the FAT RFR.

A follow-up study was performed by CPAT after the RFR. The study involved analyzing the results of FAT RFR Run 4, which dealt with the trajectory prediction accuracy implemented in ERAM's flight data processing, and Run 5, which involved the strategic conflict prediction accuracy implemented in ERAM's conflict probe tool (Paglione et al. 2008a). The tools that computed trajectory accuracy metrics for Run 4 were developed by CPAT, and the tools to evaluate the Run 5 data were developed by LM; however, CPAT has developed its own set of tools to measure the accuracy of strategic conflict predictions that have been used by CPAT in other tasks. A statistical approach was used to decide whether there was significant degradation in ERAM when compared with the legacy URET system. The purpose of the study was to further inspect the performance of ERAM, investigate areas where ERAM did indeed degrade from the legacy system, and provide an overview of the results to the FAA.

FAA/Rowan University collaboration

At the end of the fall 2004 semester, CPAT teamed with the SEGV Research Group established in the Department of Computer Science at Rowan University. Under a CRDA, the FAA provided, as government furnished equipment, desktop personal computers and Linux servers, and Rowan University established the FRATR Lab. The equipment matches the characteristics of the computers on which the software would finally be installed to accommodate easier deployment.

Figure 1 displays the overall structure of the partnership. The SEGV director negotiates with the FAA the details of the project(s) prior to their introduction into the classroom and coordinates the roles of the graduate and undergraduate students based on the scope and goals of each project. Being the liaison between the FAA and SEGV, the graduate students play roles on both sides: On the FAA side they schedule meetings and elicit new requirements from the users based on the FAA needs, and on the SEGV side they contribute by sharing the management of the projects and the mentoring of the undergraduate students participating in the projects. When they become very well accustomed to the projects' details, the graduate students play the role of the customer, thus relieving part of the workload of FAA managers. The graduate students perform installations and maintenance, and assure the smooth transition of the projects' versions from one undergraduate team to another.

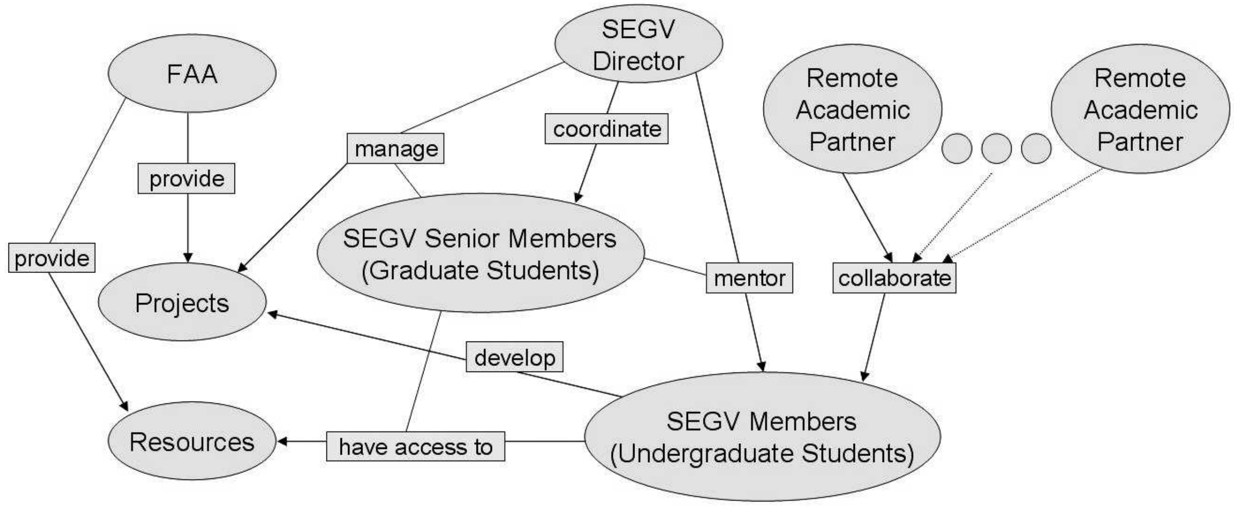

Figure 1. Overall partnership structure.

The partnership structure is flexible to allow easy addition of other academic partners. During the spring 2008 semester, we added Fairfield University students to our collaboration. Twenty students from both universities worked together in adding new functionality to existing FAA tools.

Visualization tools for testing and evaluation

A vast amount of data is generated when testing air traffic decision support software. During the T&E process, normally, data reduction and analysis (DR&A) tools are used to process the data and determine whether the software's (system's) performance is acceptable. Assuming the input data into the tools are correct, and the tools are implemented properly, the software's performance will be derived correctly; otherwise the results will be erroneous. In an attempt to prevent this case of "garbage in, garbage out," visualization tools can aid T&E analysts in validating the data. Information visualization is the visual representation of abstract data to help the user understand the data more effectively (Tufte 2001). This section presents two visualization tools that have been used in recent T&E procedures.

Trajectory graphical user interface

As previously mentioned, DSTs are used to assist air traffic controllers in the separation of air traffic. DSTs predict aircraft flight paths (trajectories) using the Trajectory Predictor and foretell potential conflicts using the Conflict Probe (CP). A trajectory is a four dimensional (latitude, longitude, altitude, and time) prediction of an aircraft's flight path. The accuracy (i.e., how close to the actual flight path's time and proximity) of trajectories generated by DSTs determine their overall performance; hence the accuracy of trajectories is the subject of the T&E process. The performance accuracy of trajectories is quantified by comparing the trajectories to the actual flight paths they predict and computing a set of error metrics (Paglione and Oaks 2007). Various algorithms and relational databases have been developed to investigate and calculate the error metrics of trajectory prediction.

Trajectory Graphical User Interface (TrajectoryGUI) is a visualization tool developed in the FRATR lab, currently used by the CPAT to evaluate the accuracy of predicted trajectories (Santiago et al. 2005). Previously, analysts would have to manually collect the trajectory accuracy results from the database, organize it for analysis, and then finally analyze the results. Using TrajectoryGUI, the process of validating the T&E metrics results are expedited because it allows the analyst to focus on evaluating the data only. TrajectoryGUI provides a graphical user interface to easily choose the data to visualize and automatically formats the data. An analyst can use TrajectoryGUI to package the trajectory accuracy results and illustrate reasons for inaccuracies.

TrajectoryGUI was entirely developed through the collaboration between the FAA and SEGV. TrajectoryGUI allows the analyst to create two-dimensional plots of flight track and trajectory error data fields, such as X–Y (latitude vs. longitude) and T–Z (time vs. altitude). Each plot can contain multiple actual flight paths, and each flight path can contain multiple trajectory paths. Illustrations of TrajectoryGUI and how it was used in support of the T&E of ERAM will be presented in the section titled "Evaluation of trajectory prediction accuracy."

Flight graphical user interface

Conflict probes provide air traffic controllers with predictions of conflicts (i.e., loss of minimum separation between aircraft, normally five nautical miles) within a parametric time (e.g., 20 minutes) into the future. Accuracy T&E requires detailed analysis of the conflict probe's predictions. The ultimate goal is to improve the accuracy of these predictions. The accuracy of a conflict probe is measured by a set of metrics involving the accuracy and timeliness of predicting conflicts and the reduction of falsely predicted conflicts.

Flight Graphical User Interface (FlightGUI) is a visualization tool developed in the FRATR lab, currently used by the CPAT to test the conflict prediction performance results of CPs (Santiago et al. 2006). As is the case with TrajectoryGUI, FlightGUI allows the analysts to focus primarily on the validation of a CP's metrics results, and not the querying or managing of the data. Additionally, the visualization provides a display in which the analyst can gain a better understanding and overview of the results, in comparison to the analyst having to perform a collection of difficult database queries, and standard spreadsheet data calculations and analyses.

FlightGUI animates the flight paths of aircraft by displaying their spatial–time relationship to each other during an encounter of a flight pair. An encounter is a precursor event to a conflict where a flight pair loses minimum separation that is greater than a conflict (e.g., 40 nautical miles) and is only for analysis purposes when testing conflict probes. FlightGUI indicates when a conflict occurs by encircling the conflicting flights (i.e., nonadherence to minimum separation standards), which aids the analyst in noticing the conflict; then the analyst studies its characteristics by analyzing the information about the aircraft in tabular form. This allows the analyst to study whether the conflict has been accurately predicted. Furthermore, the analyst has the ability to animate the encounters (nonconflict events) to study the characteristics of flight pairs that were on the edge of becoming a conflict and whether the CP falsely predicted this nonconflict event as an imminent conflict. Examples of how FlightGUI was used in the study reviewing the results of the Flight Data Processing/Conflict Probe Tool ERAM Run 4 and 5 appear in the next section.

Applications in testing and evaluation

In September 2007, the FAA successfully implemented the ERAM formal RFR and accepted the new system. Following the RFR, CPAT was tasked to perform a follow-up study examining the RFR trajectory and conflict probe accuracy results. During this study CPAT utilized its collaborative partnership with Rowan University, which had already been established, to bolster its capabilities, and inexpensively increase manpower and laboratory resources. The major purpose of the study was to examine the test results and provide an overview of the performances. This section describes how two academically developed visualization tools were used in the T&E of ERAM's DST.

Evaluation of trajectory prediction accuracy

The first analysis of the study was to investigate the vertical accuracy of ERAM trajectories. Two main requirements of the ERAM trajectory modeler were to be at least as accurate as URET (a) during level phases of flight, as well as (b) in the transitioning phases of flight. The performance of ERAM compared to URET is quantified by applying statistical analysis to a set of accuracy metrics. By investigating outliers on a flight by flight level, the analyst has the ability to not only uncover errors in the ERAM system itself but also in the set of offline support tools that process the test results and calculate the error metrics for postanalysis. This section details application examples of how TrajectoryGUI aided test analysts in evaluating the trajectory prediction accuracy of ERAM, as well as validating the test error metrics.

In this example, the aircraft is an Airbus A320 flying from Orlando International Airport, Orlando, Florida, to Washington Dulles International Airport, Washington, D.C. (MOC). The actual flight path and trajectories generated by ERAM are shown in *Figure 2*. *Figure 2a* depicts the vertical profile of the flight while in the Washington D.C. Air Route Traffic Control Center. *Figure 2b* illustrates the horizontal profile as it makes its approach to the MOC airport. For both plots, the red path is the actual flight path and the series of other paths are the trajectories. Each trajectory is identified by its trajectory build time, which is the time (seconds in the day) in the day the trajectory was generated. For this aircraft, ABC142_428, there are three trajectories: 78436s (dark blue), 78820s (green), and 78998s (light blue). The aircraft is flying at its cruise altitude of Flight Level (FL) 370, and at time 78840s the aircraft begins its arrival descent. The active trajectory when it begins its descent is 78820s, and as shown in *Figure 2a*, the trajectory correctly predicts the descent. Next, the aircraft descends to FL340 as it was instructed to do by the ATC, and remains level until time 79310s. When the aircraft begins to descend from FL340, neither the active trajectory, nor any previous trajectories, correctly predict this event. The trajectory predicted had the

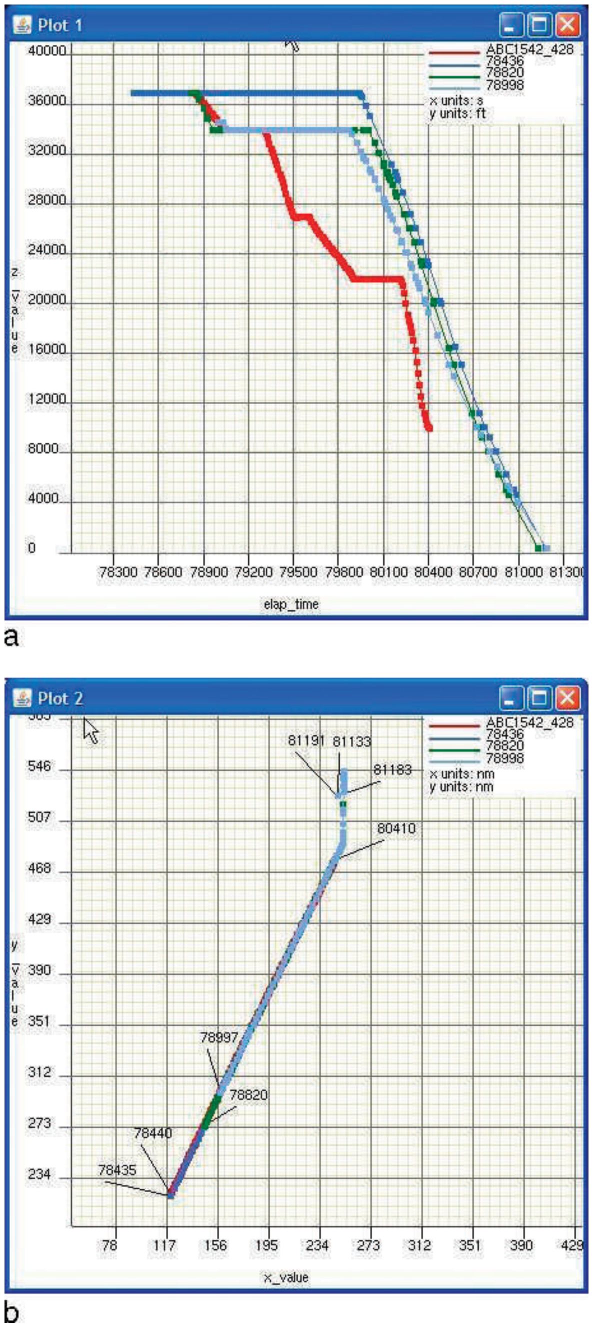

Figure 2. TrajectoryGUI. (a) Vertical and (b) horizontal profile of flight examined during the ERAM RFR study.

aircraft continually descending from FL340 to touch down at the MOC airport, when in fact the aircraft flew in a series of two additional level off periods, and when regaining descent clearance, descended much faster than what was predicted. This case resulted in an average vertical error of −5,608 feet, meaning the actual flight path was below the trajectory predictions. This was indeed an outlier and was a candidate for reporting to ERAM developers and reporting in the study. In contrast, the horizontal profile of this aircraft, shown in *Figure 2b*, clearly resembles an accurate prediction because the visualization represents overlapping paths, indicating that ERAM correctly predicted the horizontal path of the flight.

Utilizing the user-friendliness of TrajectoryGUI, the analyst was able to gather this information by a series of simple user interface selections from the visualization tool. The analysts were able to use TrajectoryGUI to investigate cases like the aforementioned, and many others, during the ERAM RFR study at a minimal cost of time and effort. The alternative is to use different methods of extracting the data, plotting, and performing the calculations; TrajectoryGUI achieves these features all in one system.

Evaluation of strategic conflict probe performance

The second analysis of the study was to evaluate the performance of the strategic conflict probe. Six requirements involving the accuracy of the strategic conflict probe were applied, three to aircraft-to-aircraft events and the same three to aircraft-to-airspace events. These requirements were used to ensure that ERAM (a) predicted conflicts in a timely fashion (i.e., predict conflict approximately 5 minutes before occurring), (b) minimized the number of missed conflict alerts (conflict occurs, but is not predicted), and (c) reduced the number of falsely predicted conflict alerts (conflict is predicted, but does not occur) for both types of events. This section introduces application examples of how FlightGUI was used to evaluate ERAM as a DST for ATCs, and validate the RFR test results.

It is important to have correctly functioning support tools if you are to correctly evaluate the performance of any system. During the ERAM RFR study, several discrepancies were found in support tools developed to calculate the performance of ERAM's strategic conflict probe. FlightGUI, in many ways, was a key factor in discovering these discrepancies. Although there were several discrepancies, details of one key discrepancy are presented in the next paragraph.

In review, a strategic CP predicts potential conflicts sometime in the future (i.e., 20 minutes), and a conflict is the loss of minimum separation by an aircraft pair. Furthermore, if an aircraft within a conflict is not adhering (i.e., adherence age less than 13 minutes) to its known ATC clearance, the conflict is discarded and not considered in the measurement of a strategic CP's performance. Adherence age is the amount of time (normally in seconds) the aircraft is not following its known clearance and has been studied by CPAT in previous work (Oaks 2005).

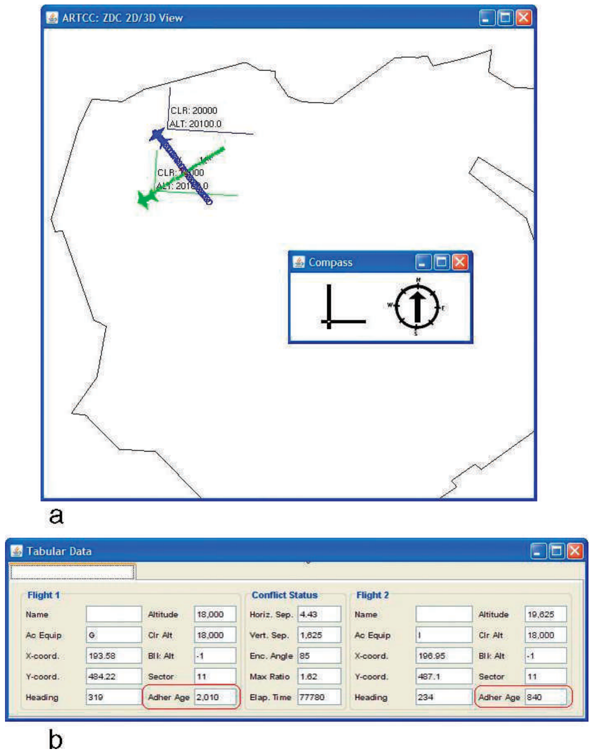

Figure 3. FlightGUI. Flight path of erroneously discarded conflict due to out of adherence. (a) The Visualization Window details the flight paths of this conflict. (b) Tabular data window details the characteristic of the conflict at the start of the conflict.

Through the use of FlightGUI during the study, the analyst was able to interface the track data for offline animation of a conflict, as well as interface the database storing the adherence values for the aircraft. *Figure 3* illustrates a case where a conflict occurred, and the adherence ages for both aircraft were greater than 13 minutes (see red callout in tabular data window). This conflict was not correctly accounted for in the ERAM RFR test results because LM's support tool considered the aircraft to be out of adherence. The use of FlightGUI confirmed this discrepancy and helped find six similar cases. This had large ramifications for the T&E of ERAM during the RFR, and, in fact, called for the change of passing the aircraft-to-aircraft missed conflict alert requirement to failure because conflicts that had no prediction were erroneously discarded in the data reduction and analysis process. This is just one application example of how FlightGUI aided in the ERAM RFR study; others are presented in the study itself (Paglione et al. 2008a).

Success Stories

The collaboration allowed Rowan University to be selected as the winner of the 2008 FLC Northeast Regional Industry/Non-Federal Government/University Award. This award recognizes an American-owned company, a nonfederal government entity, or a university within the region that has made outstanding efforts to promote the transfer of federal technology during the previous year. Since the inception of the collaboration, 35 undergraduate members of the SEGV research group have taken advantage of the partnership with the FAA and have participated in projects in the FRATR lab. All undergraduate students have been recognized with certificates of appreciation during specially arranged presentation sessions at the end of the corresponding semesters. The students have also presented their work and received recognition on campus, during Rowan's Science, Technology, Education, and Mathematics Student Research Symposium.

The experience accumulated during the development of the products and the certificates of appreciation the undergraduate students received helped the majority of them secure jobs in the aviation industry and similar industries. In fact, at least 11 of the 35 undergraduate students who participated in the collaboration received offers of employment from FAA contractors. In addition, the experiences gained by working on the projects propelled some students into graduate school. Together with the mentoring experience they accumulated, the graduate students who benefited from the co-op positions have positioned themselves as prime candidates for quality jobs as government employees. Graduate students were also given the opportunity to present the results of the work of the partnership at national aviation conferences.

Conclusion

This article presented a successful integration of government and academic organizations established to improve abilities in the testing and evaluation of air traffic decision support tools. These tools are crucial to the efficiency and safety of the national airspace system. The locations of these efforts ranged from the William J. Hughes Technical Center in Atlantic City, New Jersey, and to the FAA/Rowan Air Transportation Research Laboratory in Glassboro, New Jersey. Furthermore, two jointly developed visualization tools were presented, which were used during the post-RFR ERAM study, detailing the accuracy of ERAM's trajectory predictor and strategic conflict probe. TrajectoryGUI and FlightGUI proved to be helpful to the T&E analysts performing the study. Also, TrajectoryGUI and FlightGUI have been used by CPAT in support of other research activities (Paglione et al. 2006a, 2008b).

Partnering with academia proved to be less expensive than partnering with industry and offered more flexibility in collaborating, and at the same time improved the FAA's T&E capabilities during the ERAM RFR analyses. The award-winning collaboration has gained positive exposure, produced advances in FAA's T&E processes, and has offered students experiences and opportunities in the real world. ❑

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ITEA Best Paper

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Testing in a Joint Environment 2004–2008: Findings, Conclusions, and Recommendations from the Joint Test and Evaluation Methodology Project

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The Office of the Secretary of Defense chartered the Joint Test and Evaluation Methodology project to institutionalize testing in a joint environment. The project has now finished most of its major activities. In this article we describe our key accomplishments, findings, conclusions, and recommendations. Testing in a Joint Environment refers to tests of military systems as participating elements in overarching joint systems of systems. The concept first appeared in Strategic Planning Guidance and was formally introduced as Department of Defense policy in a roadmap signed by the Deputy Secretary in 2004. Several working groups were formed to implement the roadmap. The Joint Test and Evaluation Methodology project was initiated in 2005 to continue efforts of the methods and processes working group. Throughout the past three years we have developed, tested, and evaluated a number of methods and processes for defining and using a distributed live, virtual, and constructive joint test environment to evaluate system performance and joint mission effectiveness. We briefly describe those processes, what we learned by testing them, and the extent to which they improve the ability to conduct tests, across the acquisition life cycle, in realistic joint mission environments. We also describe the results of two large-scale distributed tests—INTEGRAL FIRE 07 and Joint Battlespace Dynamic Deconfliction 08—which used mixes of live, virtual, and constructive elements to test a number of systems in joint environments. Several challenges remain, and we make recommendations to continue progress toward the goals of testing in a joint environment. The Department's long-term strategy calls for evaluations of joint system effectiveness throughout all phases of all weapon systems' development and deployment.

Key words: Acquisition; joint test environment; joint mission effectiveness, testing, methods, processes, planning; planning; rehearsal-of-concept (rock) drills; simulations, live, virtual, constructive.

The Joint Test and Evaluation Methodology (JTEM) project was initiated in February 2005 by the Director of Operational Test and Evaluation (DOT&E). We were directed to investigate, evaluate, and make recommendations to improve the ability to test across the acquisition life cycle in realistic joint mission environments. Our focus was to be on methods and processes for testing in a joint environment. The concept of "testing in a joint environment" comes from U.S. Department of Defense (DoD) 2006–2011 Strategic Planning Guidance for Joint Testing in Force Transformation. It refers to tests of military systems as participating elements in overarching joint systems-of-systems. Over the past three-plus years, we developed and applied several processes and test methodologies. Many are refine-

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ments to current test and evaluation procedures; but some are not. In this article we discuss three of the more significant changes in test and evaluation (T&E) procedures needed to make testing in a joint environment a routine part of defense system development. First, testing in a joint environment must be integrated into each acquisition program's T&E strategy. Second, test events take on several new dimensions, especially during development testing. And third, the evaluation of test results brings together warfighters and developers in new and challenging ways.

Because the concept of testing in joint environments originated in transformation planning guidance, it is fundamentally transformative in nature. And transformation, we discovered, is hard. The DoD's goal is to define, develop, and then test new military systems in the context of how we fight, i.e., jointly. But while war fighting is now an inherently joint process, defense systems acquisition is inherently not. And that is the overarching challenge to testing in a joint environment. The *Testing in a Joint Environment Roadmap* (DoD, 2004a), coordinated by DOT&E in 2004, remains the only official document directing testing in a joint environment. The roadmap identifies changes to policy, procedures, and test infrastructure needed to routinely conduct T&E in joint environments. The approved roadmap makes testing in a joint environment clear Department policy and calls for all programs, regardless of acquisition category, to demonstrate their joint capability early and throughout their respective development cycles. But acquisition programs, by statute, are initiated, funded, and managed within military services. The roadmap still defines a desired end state, but the Department has yet to bridge the gap between this end state and current practice. This theme is echoed in conclusions and recommendations discussed later.

A key aspect of JTEM's direction from DOT&E was using a distributed live, virtual, and constructive (LVC) joint test environment to evaluate system performance and joint mission effectiveness. The *Testing in a Joint Environment Roadmap* authors quickly concluded that no single test facility could consistently provide sufficiently robust joint environments. The authors saw modern networks and rapidly improving simulations as the means to overcome single-facility limitations. Networks could make several different and geographically dispersed test facilities appear as one. Networks also allow operator or hardware-in-the-loop simulations (sometimes called *virtual* simulations) to substitute for live systems and digital computer simulations (sometimes called *constructive* simulations) to substitute for live or virtual systems in a joint test environment. Combinations of live, virtual, and constructive simulations—linked through networks into a single distributed environment—could then form *LVC* joint mission environments for testing. A substantial portion of JTEM resources went to systems engineering activities used to integrate simulations into a distributed environment. As it turned out, these technical activities were relatively easy compared to the nontechnical challenges discussed in this article.

During the past three years we used various activities as settings for testing and evaluating evolving versions of methods and processes. Some observers have likened this to making a movie about people who are putting on a play. Just as the play is a backdrop for the movie characters, JTEM activities were backdrops to evaluate processes for testing in a joint environment. Initially we used Rehearsal of Concept (ROC, sometimes spelled *rock*) drills (U.S. Marine Corp, 2001) for initial process evaluations. Rock drills involved representative users conceptually walking through processes without actually conducting a test. We used these drills for initial process shakedowns to uncover major problems before applying the processes during distributed LVC events. In 2007 the distributed event was the Air Force's INTEGRAL FIRE, and in 2008 it was the Army's Joint Battlespace Dynamic Deconfliction (JBD2). Potential users of JTEM processes applied selected processes during the planning and conduct of these events. Each event included live, virtual, and constructive representations of systems that together accomplished one or more joint missions. JTEM selected some of these systems and joint missions as notional test items. We then used data collected during the events to evaluate system performance and mission effectiveness in a joint environment.

The emphasis in this article is on the more difficult future challenges facing the DoD if testing in a joint environment is to become an achievable goal. In terms of current processes, these challenges start with Test and Evaluation Master Plans (TEMPs). The next section explains the planning information needed in TEMPs to make testing in a joint environment an integral part of an acquisition program's T&E strategy. Then we describe some enduring relationships among test organizations needed to make distributed LVC testing a routine part of development and operational tests. Next we identify how results of tests in joint environments must be evaluated concurrently by developers, operational testers, and end users. We conclude with some recommendations that span these three areas. None of these changes is prohibited by current policy, directives, or law. However, they represent transformative, cultural changes, and they may require substantial commitments of resources.

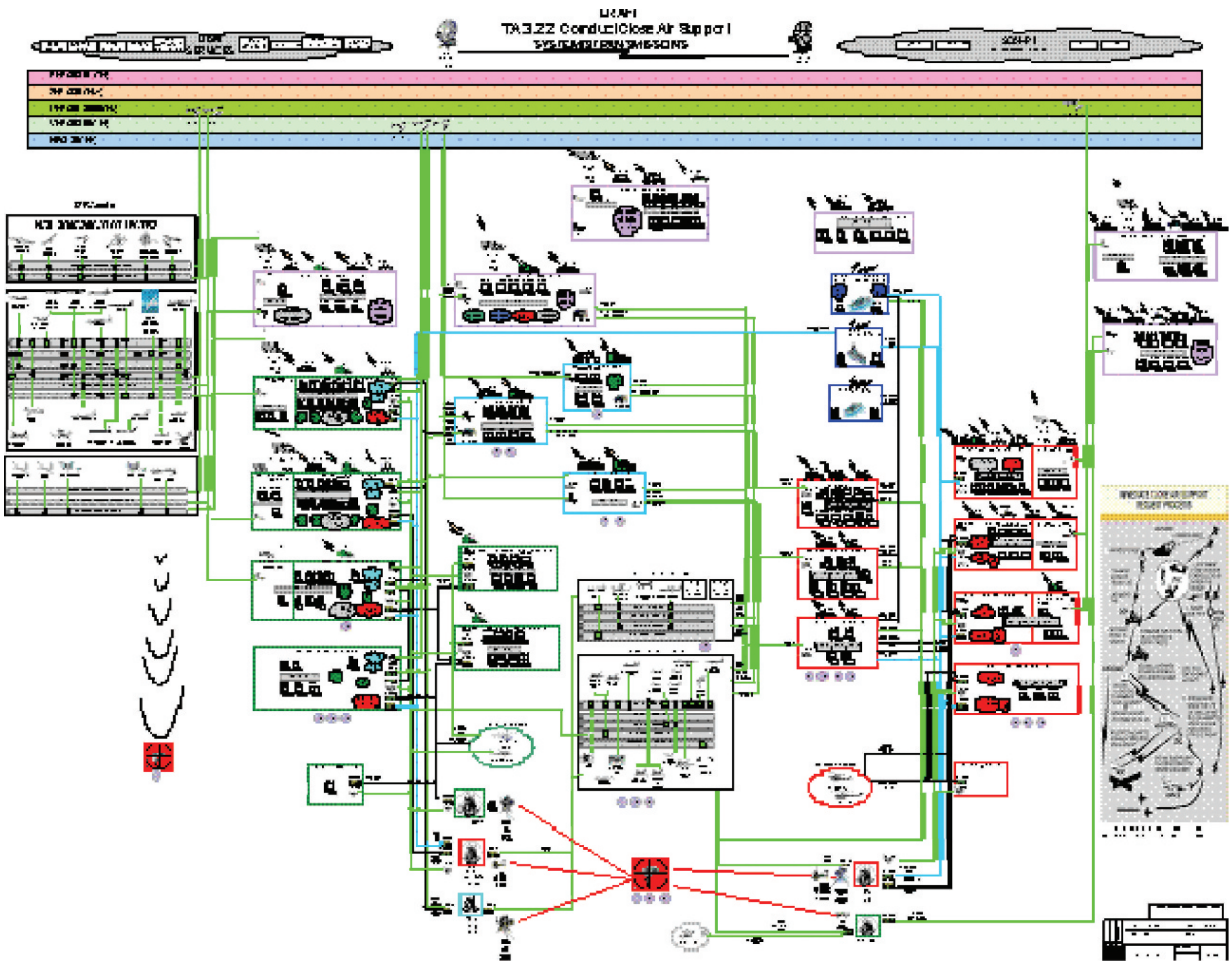

Figure 1. JFCOM Joint Architecture for close air support.

T&E master plans

From the beginning we recognized the importance of addressing testing in a joint environment in each program's TEMP. For one thing, if testing in a joint environment is not part of the TEMP, then testing in a joint environment is not resourced. But while integrating testing in a joint environment into master plans seemed straightforward at first, it turned out to more difficult than we expected. We gathered information on TEMP modifications for testing in a joint environment during workshops with the Operational Test Agencies (OTAs) and as part of early planning for one of our distributed test events. The OTA workshop concentrated on those parts of a TEMP of most interest to an OTA—Initial Operational Test and Evaluation (IOT&E) to support a full rate production decision, operational assessments conducted periodically throughout development testing, and resourcing for both. Early planning for our second distributed test event attempted to broadly define the joint operational context for the tests using guidance from current joint doctrine and tasks.

During our workshop, the OTAs had many questions about how to build a TEMP incorporating testing in a joint environment, but two are particularly noteworthy. Senior technical leaders were looking for guidance on how to insert testing-in-a-joint- environment events into the overall test schedule. One sensible answer is to have OTAs conduct testing in a joint environment during traditional Operational Assessments (OAs) or even early operational assessments. OAs do not carry the same restrictions on simulation use as IOT&E. Hence OTAs could provide valuable operational insight into design alternatives when the developer may be working with relatively easy-to-change constructive or virtual prototypes. And if such events are to be conducted in realistic joint mission environments, then OTAs are better positioned to plan them. This leads to the second question: Because joint mission environments necessarily include tactics, tech-

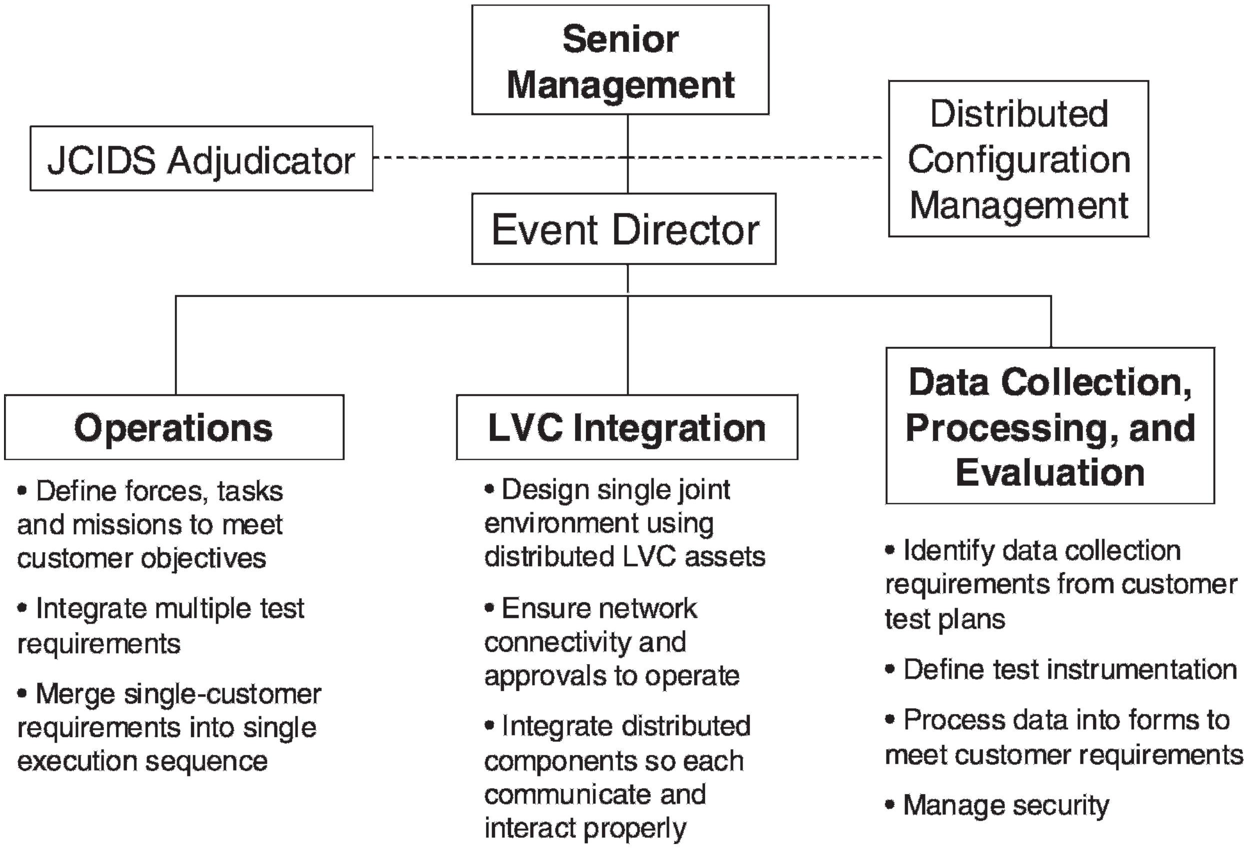

Figure 2. Most effective functional organization based on JTEM events.

niques, and procedures (TTPs) for employing the system under test, how do you plan for situations when current TTPs are clearly inappropriate for the new system? A complicating factor, as we discuss later, is that system effectiveness may depend on TTPs, and vice versa.

We also addressed some TEMP information during early planning for our second distributed event. The Army used the JBD2 event to integrate distributed components in support of future test requirements. Working with Army event coordinators, our intent was to define a broad joint operational context for the test based on current joint doctrine (DoD, 2004b) and the Universal Joint Task List. However, as might be expected, we found current doctrine and training tasks a poor fit for future capabilities. We were also hampered by the lack of documentation from the Joint Capabilities Integration and Development System (JCIDS) (DoD, 2007). Capability Development Documents and Capability Production Documents, for example, should address future doctrine adjustments that will be needed when the capability is fielded. And certainly these doctrine requirements should be used as a starting point for testing-in-a-joint-environment operational concepts. When available and appropriate, another good starting point would be joint architectures provided by U.S. Joint Forces Command (JFCOM). *Figure 1* shows an example for close air support (DoD, 2003).

But normally the effectiveness of proposed future doctrine will be uncertain until after some field trials. We have concluded that a sensible approach to master plans for testing in a joint environment is to test nonmaterial doctrinal concepts along with the material solution to a joint capability gap. But this is not how most acquisition programs are currently managed.

Relationships among test organizations

An important objective of JTEM distributed events was to evaluate the effectiveness and suitability of working group structures. Our goal was to use these evaluations to recommend organizational relationships and functions appropriate for a persistent distributed LVC test *range*. This *range* should be able to support future testing in a joint environment on a regular basis. INTEGRAL FIRE used three primary working groups and one overarching group to coordinate among the first three. JBD2 created six primary working groups. Combining lessons learned from these two constructs, we identified three basic functional areas needed to effectively conduct distributed LVC testing. Within a single test organization, these activities might fall within current range management, range operations, and data management units. For our distributed events, involving multiple test organizations, the functional areas were operations, LVC integration, and data-related functions. *Figure 2* includes a few more details. Two fundamental assumptions behind *Figure 2* are (a) multiple test customers are participating in each test event, and (b) each individual customer has an approved test plan. The latter mirrors typical single-range procedures where a customer cannot enter the scheduling process without an approved test plan or similar document. Test organizations should consider some permanent cross-organizational relationships to accomplish the functions in *Figure 2*, including approval procedures for test plans requiring distributed LVC events.

A few other aspects of *Figure 2* require some clarification. For example, JCIDS adjudication would entail resolving real or apparent inconsistencies among joint mission requirements. Distributed configuration management is clearly necessary and might best be handled by a group encompassing configuration managers at participating test organizations. We should also point out INTEGRAL FIRE and JBD2 had compressed timelines and focused on single events at predetermined, fixed dates. Activities were necessarily focused on constructing distributed environments, executing operational missions, and collecting data with whatever assets happened to be ready on test day. Early test planning was rushed, and detailed test planning was inconsistent across events and customers. INTEGRAL FIRE had fewer problems, due in no small part to its overarching coordinating group. Hence such a coordinating function will be critical to the success of future distributed LVC tests.

Evaluation of test results

We defined notional test items—systems and associated joint missions—during our distributed LVC events to create opportunities to apply our proposed processes for the evaluation of test results. For example, INTEGRAL FIRE included a constructive network enabled weapon (system under test) employed in support of joint close air support missions. INTEGRAL FIRE also included a constructive surface-to-surface missile used for joint fire support missions (DoD, 2006). During test trials, calls for fire support and air support requests were sequenced to intentionally create airspace conflicts. Conflicts were then resolved using current joint airspace control doctrine (DoD, 2004). The constructive network enabled weapon (NEW) was an air-launched, bomb-

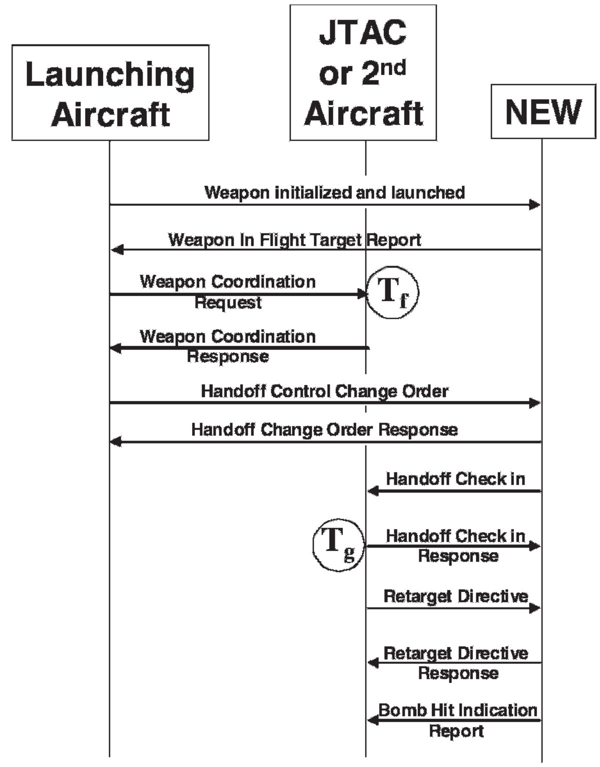

Figure 3. Procedures used in INTEGRAL FIRE to handoff weapon control.

on-coordinates, sub-500-pound-class guided bomb with data link capabilities. The weapon's data link mode with third party targeting was evaluated in these tests. In this mode, target coordinates stored in the weapon are updated after launch by either another aircraft or a ground-based Joint Terminal Attack Controller. Before the weapon will accept updated coordinates, the launching aircraft must hand off control of the weapon to one of these *third parties*. The constructive NEW model was designed to implement handoff procedures contained in draft operating concepts (Air Combat Command, 2006). These procedures are outlined in *Figure 3*.

For the purposes of providing an example application of JTEM evaluation processes, postlaunch handovers of NEW control were conducted to determine the ability of pilots and Joint Terminal Attack Controllers to perform handoff functions in a joint mission environment. Each trial included a postlaunch handoff of NEW control by the launching aircraft. Prior to weapon launch, pilots of the launching aircraft coordinated handover of weapon control to either a Joint Terminal Attack Controller or a second aircraft. Handoff time (time interval from T_f to T_g) measured the effectiveness of each handoff. Test results showed that handoffs to the second aircraft were relatively fast when the airspace control volume was small, but relatively slow when larger airspace control volumes were used. This result indicates interdependence between joint airspace control doctrine and weapon design mechanization during the test. The system-acquisition question is: Should the developer modify the weapon design or should the operational community modify doctrine? Who decides? We recommend the DoD clarify responsibilities to account for these inevitable material–nonmaterial dependencies. We also believe better guidance is needed, in general, on how evaluations of joint mission effectiveness are to be used by milestone decision authorities to support decisions such as continued development, full-rate production, or fielding.

Summary

Through our rock drills, distributed LVC events, and related activities, the JTEM project has been able to sustain some momentum toward institutionalizing testing in a joint environment. In addition to the conclusions and recommendations discussed, our final report will contain many other technical and nontechnical findings. For example, test infrastructure investments are currently not managed with a distributed, joint test environment in mind. And the opposing-force side of the equation remains largely ad hoc (although the Test and Evaluation Threat Resource Activity has jumped in to tackle some aspects of the problem). Overall, JTEM has contributed to building the foundation for a solid community of interest for distributed LVC testing. Test organizations across the services are now better prepared to support testing in a joint environment when requirements are formally communicated to acquisition program managers. ❑

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ITEA Best Paper

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High Speed Photography and Digital Image Correlation for the Study of Blast Structural Response

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The blast response of structures is difficult to measure because of the high speed and transient nature of the deformation and also because of the severity of shock effects. Measurement approaches using strain gauges and accelerometers provide pointwise information only and may be adversely influenced by shock-related noise. High speed photography in combination with digital image correlation, however, allows full-field, noncontact measurements of the dynamic response of structures and structural components to blast forces. The fundamental concepts and requirements for image correlation measurements are briefly described along with results of displacement accuracy tests. Dynamic measurements of blast response are presented for a steel witness plate, a thin aluminum panel, and a section of aircraft skin in the cargo bay of a commercial aircraft. The spatial and temporal characteristics of the transverse deflection and in-plane strain for these test surfaces are presented and discussed. Imaging frame rates in the range 9,000–10,000 frames per second are used to measure transverse surface deflections and velocities as large as 150 mm and 300 m/s, and plastic strains in excess of 8%.

Key words: Commercial aircraft; deflection; explosions; measurement; mitigation; plastic strains; surface deformation; vulnerability.

Because of the ever present potential for terrorist attack using explosives, it is important to evaluate the vulnerability of structures to blast forces. In some cases it may also be possible to develop strategies for mitigating blast structural damage and catastrophic failure. The most important component of vulnerability assessment or mitigation development is the ability to either predict or measure the response of a structure to a particular blast load. Both numerical modeling and test measurements of blast structural response are difficult due to the very short duration and high speed nature of the event; however, these are even more difficult in the case of lightweight aircraft structures. In part, this is because these structures are generally much more structurally complex, involving a three-dimensional arrangement of numerous riveted or bonded joints. Also, the lightweight construction leads to greater blast-induced velocity as well as larger deformation and strain. The strains resulting from blast loading are often well beyond the plastic yield

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point of the structural frames and skin. Plastic strains of several percentage points are common. The large plastic strains, and possibly crack initiation and extension, in structural components make accurate modeling of the structural response very challenging. However, measurement of the blast response of an aircraft structure is also very difficult. In addition to the challenges posed by the highly transient nature of the response, there may be only one opportunity to gather useful data if the structure under test is damaged or destroyed. This means that optimal placement of sensors such as strain gauges and accelerometers on the structure is critical if key data are to be collected from a single test. This is especially demanding owing to the pointwise nature of the information available from these sensors and the rather unpredictable spatial response characteristics that may result from a plastically deforming or failing structure. Indeed, the identification of critical stress and failure locations on the structure may be the primary motivation for performing the test. Further, attached sensors of even small mass can separate from the structure or they can subtly perturb the local response of lightweight aircraft structures when shock-induced accelerations are high.

A full-field noncontact measurement technique greatly increases the probability that data will be captured in critical areas of the structure without distortion of the desired test conditions. A market survey of full-field noncontact methods was conducted at the Transportation Security Laboratory (TSL) at the W. J. Hughes Technical Center in the fall of 2005. Holographic and speckle pattern interferometry and digital image correlation were considered in the survey; however, it was found that only digital image correlation is capable of resolving the large displacements that typically result during blast-induced deformation of aircraft structures. Development of this technology began in the 1980s (Bruck et al. 1989; Chu et al. 1985; Sutton et al. 1983, 1986), but it only evolved into a practical measurement tool in the 1990s (Helm, McNeil, and Sutton, 1996; McNeil et al. 1997) owing in part to the rapid advancement and widespread availability of inexpensive computational power. More recent applications of image correlation for measurements of high speed crack propagation and ballistic impact are discussed in Kirugulige, Tippur, and Denney (2007), McNeil et al. (2003), and Schmidt et al. (2005). Some preliminary measurements of structural blast response, including aircraft structures, were described in our previous research (Nansteel and Chen, 2007), and the present article builds on that study by providing new results for various types of explosives and structures.

High speed photography in combination with digital image correlation has been adopted by the TSL as a tool for measuring the response of aircraft structures to blast effects. After rigorous accuracy validation of the image correlation system, this technique was used for measuring the full-field displacement response of structural panels of various constructions to a wide range of load conditions. Panels included simple and sandwich construction aluminum panels, Kevlar–felt composite blast mitigation panels, a steel witness plate, and aircraft fuselage skin panels supported by airframe structure. Load conditions included uniform static loads as well as blast loading from actual explosive threats of varying weight and standoff from the target panel. The purpose of each test was to directly or indirectly enhance the understanding of aircraft vulnerability or evaluate the effectiveness of mitigation strategies for commercial aircraft. Some of the measurement results are presented and discussed in this article.

Description of the image correlation measurement

Three dimensional (3D) image correlation uses stereo imaging of a patterned test surface in combination with pattern recognition and photogrammetry processes. This technology enables the quantitative full-field measurement of in-plane and out-of-plane displacement over the test surface in each photographic frame. It is only necessary that the surface pattern remain attached to the surface and the surface area under study remain within the photographic view field throughout the test event.

For image correlation two synchronized high speed digital cameras are focused on a patterned test surface. The pattern must be isotropic, nonrepeating, and high contrast. These requirements are satisfied by a random, high contrast pattern of painted-on black speckles over a white background. Painted-on speckle patterns of varying coarseness can be created by spraying paint onto the surface. However, for some large structures where a painted-on pattern is not practical, a satisfactory pattern can be created from a random arrangement of black stick-on numeric characters superimposed onto a white background. During image correlation processing of each pair of simultaneous digital images, pattern recognition is used so that each physical point on the test surface can be correlated between the two images. The high contrast speckle pattern enables the pattern recognition process by providing spatially varying gray levels that are used to distinguish between small square pixel arrays in each image. The pattern recognition procedure results in a one-to-one mapping of surface positions in the first image to corresponding positions in the second image. Then the position, in three dimensions, of each point on the surface can be determined by triangulation. This triangulation (photogrammetry) process is facilitated by a pretest calibration procedure that serves to fix the orientation of the two cameras with respect to one another in space. The calibration is carried out using multiple image pairs of a regular pattern of features with precisely known size and spacing held at various orientations with respect to the cameras. The triangulation process allows the motion of each subpixel-sized point on the test surface to be tracked in three dimensions as the surface deforms under the applied load. This process results in full-field measurement of the surface deformation relative to the unloaded, undeformed reference condition at each photographic frame. Displacements can be measured with magnitude ranging from microns to tens of centimeters at a resolution that is typically about 0.05 pixel. Additional processing of the measured displacement field, if desired, leads to the surface strain.

High speed video system

The basis of the image correlation system is a pair of Photron APX-RS monochrome video cameras. These cameras are capable of operation at frame rates up to 250,000 frames per second (fps), maximum resolution (at 3,000 fps) of 1,024 × 1,024 pixels, and shutter speeds as high as 1 μs. Each camera has 8 GB of internal memory. For blast applications the cameras are triggered by a TTL-level signal from a trigger box that in turn is triggered by the same signal that energizes the charge detonator. The cameras are controlled by a laptop PC running Photron Fastcam Viewer software, version 2.4.3.6. The PC is connected to the cameras by fiber-optic cable through a PCI fiber-optic card and expansion chassis. The PC also serves as a repository for video images that may require additional processing after the blast event. The cameras, which operate as master and slave, are synchronized at each frame except for a 108 ns time delay for the slave camera with respect to the master. Synchronization is via coaxial cable connection between the cameras.

Measurement accuracy characteristics

To establish the displacement measurement accuracy of the system, we performed a series of static displacement measurements. A speckle patterned cast iron surface plate (254 mm wide × 356 mm tall, 13 μm flatness) was used as the test surface. This plate was rigidly mounted to a rotary indexing table that allowed the test surface to be translated up to 200 mm either in its own plane or normal to itself, and rotated up to 360°. The translation and rotation accuracies of the indexing table were 51 μm and 0.05° with corresponding resolutions of 25 μm and 0.05°, respectively. The plate surface was imaged with the two

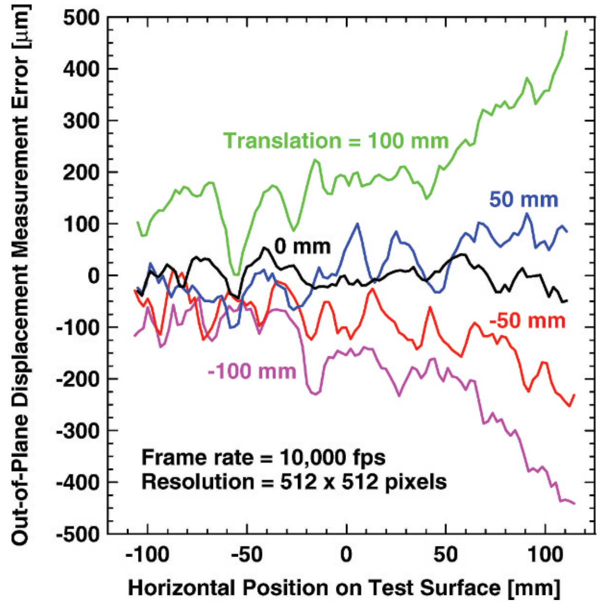

Figure 1. Displacement measurement error: out-of-plane displacement.

Photron APX-RS digital cameras operating at either 10,000 fps corresponding to 512 × 512 pixel resolution or 3,000 fps corresponding to 1,024 × 1,024 pixel resolution. Camera angles ranged between 30° and 34°. Images of the test surface at a static reference position were acquired as well other static positions corresponding to translation and/or rotation from the reference position. Image correlation measurement of the displacement from the reference position was compared with the displacement indicated by the indexing features of the table. The error in the correlation measurement, to within the accuracy of the indexing table, was the difference between these. The error characteristics of the measurement system were studied for various physical measurement parameters such as in- and out-of-plane displacement magnitude, camera angle (included angle between camera view directions), and the test surface obliqueness with respect to the cameras (the angle between the camera angle bisector and the surface normal). The effect of speckle pattern loss was also considered in anticipation of potential pattern separation from blast-affected structures in the course of testing.

Figure 1 shows the error in the image correlation measurement plotted as a function of horizontal position on the test surface for out-of-plane translations of the surface from 0 to ±100 mm using a frame speed of 10,000 fps and 512 × 512 pixel resolution. The camera angle bisector was normal to the test surface and displacement of the surface toward the cameras is considered positive. The error is plotted in *Figure 1* for a contour extending from the extreme lower-left corner of the square test surface to the extreme upper-right corner. This contour was selected to display error variation near the center of the images as well as at the extremes where error magnitudes may be larger. Displacement error data are displayed as a function of horizontal position over this diagonal inspection contour. The origin of this horizontal position coordinate corresponds to the center of the test surface while large negative and large positive values correspond to the extreme lower-left and upper-right corners of the test surface, respectively. Generally the image correlation measurement overestimates the displacement of the surface, whether or not the surface displacement is toward or away from the cameras, and errors increase with the displacement magnitude, cf. *Figure 1*. The error is smallest near the lower-left corner of the surface and greatest near the upper-right corner. The greatest errors, about 480 μm, occur for a displacement of 100 mm in the upper-right corner of the surface. The relative error in the displacement measurement here is 0.48%. For out-of-plane translations, the relative error is less than about 1% for translations greater than 8 mm. For zero translation of the surface, the error (noise level) is less than about 50 μm. In-plane displacement error was measured by translating the test surface in its own plane. These measurements show similar error characteristics to the out-of-plane case, that is, the error increased with the magnitude of the in-plane translation and the error was about the same magnitude. The same error measurements were carried out using a camera frame rate of 3,000 fps and the correspondingly greater image resolution of 1,024 $\times$ 1,024 pixels. At this increased resolution the errors in the displacement measurement were similar to those at 512 $\times$ 512 pixel resolution but with lower spatial variation in the error. Displacement error was found to vary only modestly with camera angle in the range from 20° to 50° and with the obliqueness angle (the angle between the camera bisector and the normal to the test surface) in the range $\pm$40°. This latter sensitivity is important because pattern recognition efficiency is reduced as the pattern is viewed at greater and greater obliqueness angles. To simulate speckle pattern loss, we used circular patternless patches to cover the central part of the square test surface. The effect of pattern loss on accuracy was also modest, with relative errors in the measured displacement remaining below 1% for patternless areas of 20, 40, and 60 mm.

Blast response of plates, panels, and aircraft structures

Blast structural response has been measured using image correlation for various structures. The measurements discussed further on include the dynamic response of a steel witness plate to detonation of three different types of explosive charges, the large plastic deformation of a thin aluminum panel due to attack by a spherical high explosive charge, and the blast-induced deformation of the skin of a commercial aircraft that was fitted with an internal blast mitigation liner.

Blast response of a steel witness plate

It is necessary to evaluate the vulnerability of aircraft structures to damage by explosives of various types. To accomplish this evaluation process efficiently for a wide variety of explosives, it is useful to implement the notion of explosive equivalence. This approach results in the assignment of the blast intensity (e.g., peak pressure or impulse) for the explosive under test relative to the intensity for a well-characterized reference explosive. It has been shown that under impulsive loading conditions, the peak elastic deflection of a witness plate is proportional to the total impulse delivered to the plate by the blast. Although no single blast intensity characteristic is sufficient to completely describe the equivalence relationship, blast impulse is probably the best single characteristic to use in the context of aircraft vulnerability. This is because the deflection and strain induced in a structure by an impulsive load correlates well with the magnitude of the impulse delivered to it. The elastic response of a circular steel witness plate to the detonation of bare explosive charges of several types was measured by image correlation to determine the explosive equivalence of these explosives in the sense of blast impulse.

The circular witness plate was 20.8-mm-thick heat-treated 4340 steel with tensile yield and ultimate stresses of 183 and 193 thousand pounds per square inch (ksi), respectively. The 91.4 cm (36 in.) diameter witness plate was rigidly bolted over a 76.2 cm (30 in.) diameter hole in a 12.7 cm (5 in.) thick vertical steel bulkhead with 36 three-quarter inch Grade 8 steel bolts on an 83.8 cm (33 in.) bolt circle. The bulkhead was approximately 1.85 m (73 in.) wide and 2.72 m (107 in.) high. The steel alloy and thickness of the witness plate were chosen to yield an easily measurable but elastic response when subjected to the blast loads under study. *Figure 2* shows the speckle patterned witness plate installed in the test fixture, from the camera side (opposite the blast).

The high speed cameras were symmetrically located about 5.5 m (18 ft) from the plate center and separated by about 2.7 m (9 ft), resulting in a camera angle of approximately 30°. Camera frame rate was 10,000 fps with corresponding 512 $\times$ 512 pixel image resolution. This frame rate corresponds to a 100-μs interval between consecutive images.

The witness plate response for three different explosive charge types, all differing in explosive

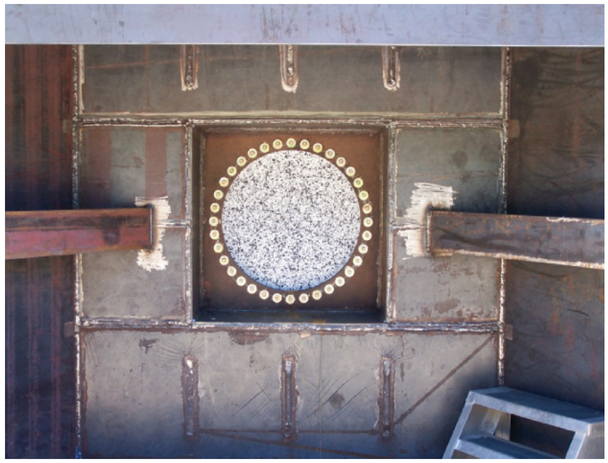

Figure 2. Speckle patterned steel witness plate and test fixture.

compound and physical form, are discussed here. These charges will be referred to as explosives α, β, and γ. The charge sizes are characterized by the charge weight. The charge weights will be referenced in terms of a coded scale of weight measurement here denoted by the symbol C. The coded weights are proportional to the actual weights; however, the proportionality factor will not be revealed for security reasons. Similarly, the standoff distance of the charge from the witness plate center is withheld for security.

A 3D contour-shape plot of the transverse witness plate deflection, measured by image correlation, is shown in *Figure 3* for a 16 C charge weight of explosive α. The color contours in this plot are correlated to the deflection magnitude, denoted by the symbol W, by the legend appearing in *Figure 3*. The *X* and *Y* coordinates in *Figure 3* are horizontal, increasing to the right, and vertical, increasing upward on the witness plate, respectively. The origin of the *X* and *Y* coordinates is at the plate center. The deformation shown in *Figure 3* corresponds to the peak deflection of the plate, which occurs eight images or 800 μs after the first image in which deformation is observed. The plate deformation is seen to be everywhere convex and is approximately axisymmetric with respect to the plate center where the deflection is 8.23 mm. The plate deformed shape was found to be similar, except for a deflection scaling factor, at other times during the response and for other charge weights of explosive α. The axial symmetry of the plate deformation suggests that the blast load distribution on the plate is also axisymmetric. The greatest transverse velocity of the plate occurs at the center in the first 100–200 μs of the first plate oscillation cycle. The mean plate velocity in this time interval is about 15.9 m/s. After this the plate velocity decreases dramatically. This early period of large plate velocity may correspond to the duration of the blast loading on the plate.

Figure 4 shows a contour-shape plot of transverse plate deflection for a 4 C charge weight of explosive β. This plot corresponds to a time that is six images or 600 μs after the first deformed image and three images before the image corresponding to peak deflection. Note that this deformation is not everywhere convex and not axisymmetric like it was for explosive α, cf. *Figure 4*. The deformed shape in *Figure 4* exhibits an area of concavity in the center region, and the peak deflection is skewed toward the upper-left quadrant of the plate. This same asymmetry is observed in all tests with explosive β. In each case the asymmetrical features of the deformation appear very early in the deflection process and quickly vanish before one-quarter of the first plate oscillation cycle is complete. From this time onward the deformation exhibits the same axisymmetric shape as seen for explosive α. The early asymmetric plate deformation shape suggests that nonaxially symmetric blast loading on the plate by explosive β has excited one or more of the higher, nonsymmetrical plate vibration modes.

Figure 5 shows the histories of transverse deflection and the first principal strain in the plane of the witness plate surface at the plate center for a 5.2 C weight of explosive β. The strain is determined by postprocessing the image correlation-measured in-plane surface displacement. In *Figure 5* positive displacement indicates motion toward the cameras, and the symbols on the two curves correspond to the transverse deflection and strain measured by image correlation for each consecutive image. The origin of the time coordinate (time equal to zero) in this plot corresponds to the last photographic image without deformation. Because of the complex asymmetric motion of the plate during the first quarter of the first oscillation, the displacement increase leading to the peak deflection is nonmonotonic, cf. *Figure 5*. The local minimum in displacement at about 700 μs corresponds to the intermittent

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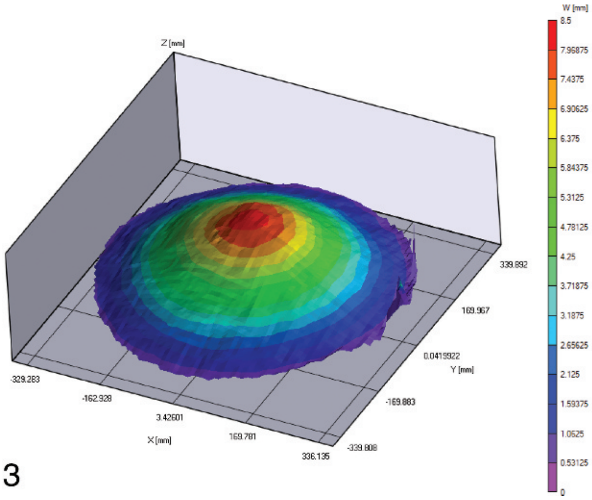

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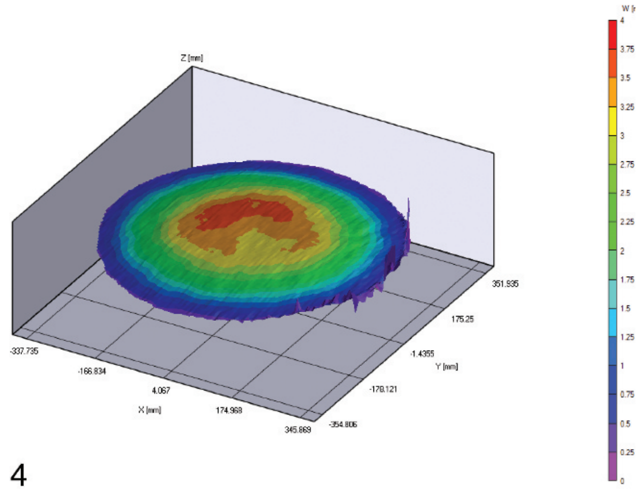


Figure 3. Contours of transverse deflection at maximum plate deflection: Explosive α, 16 C. (left). Figure 4. Contours of transverse deflection: Explosive β, 4 C (right).

deformed plate shape with central concavity as in *Figure 4*. Also note that the strain in *Figure 5* is well correlated with the displacement. Tensile strains mostly correspond to positive deflection, and compressive strains correspond to negative deflection. One obvious exception occurs at the first negative strain peak at 700 μs. This compressive strain is related to the asymmetric plate deformation shown in *Figure 4* in which the concavity at the center of the plate results in a small compressive strain there. Also note that peak tensile strain occurs quite early in the event. This peak strain, of magnitude ~4,200 microstrain (με), corresponds to the first deformed image. A slightly lower strain peak, ~3,800 με, occurs slightly later and coincides with the peak deflection of 6.93 mm. Using the principal strains 4,200 and 3,700 με measured at the plate center in the first deformed image, we find the corresponding first principal stress to be 168,000 psi. This large stress is still comfortably below the yield stress of 183,000 psi for the 4340 alloy plate.

Figure 6 shows the variation of witness plate peak deflection with charge weight for the three different explosive charges. The charge standoff from the witness plate was held fixed in all tests shown in *Figure 6*. The straight line fits for each explosive represent the data well; however, the number of samples for explosives β and γ are too small to draw any definite conclusions about linearity. The plotted data indicate that the peak deflection is most sensitive to charge size for explosive type β and least sensitive for the γ-type charges with the α-type charges falling in between, cf. *Figure 6*. It is also clear from *Figure 6* that for a given charge weight at a fixed standoff, the type β charge results in considerably greater plate deflection than the α charge and much greater deflection than the γ charge. Extrapolation of the data for explosive type γ

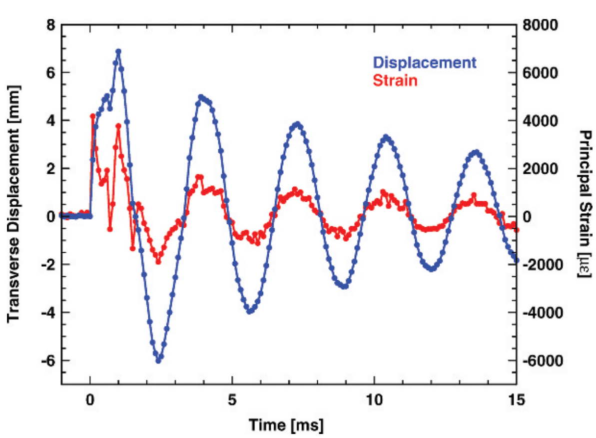


Figure 5. Transverse deflection and principal strain time history at plate center: Explosive β, 5.2 C.

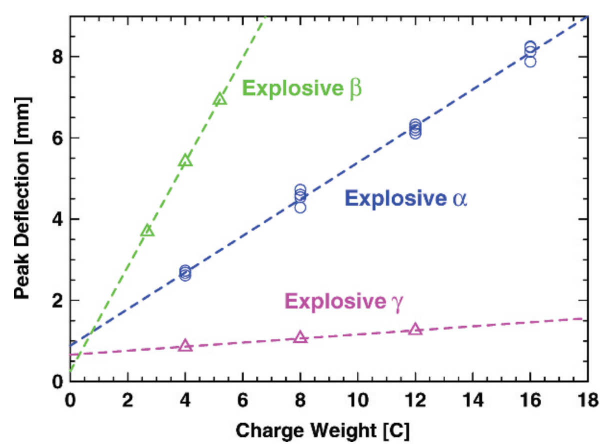


Figure 6. Witness plate peak deflection variation with charge weight.

to higher charge weight suggests that explosive α results in greater plate deflection than even four times the mass of type γ. And, explosive type β results in the same deflection as about 2.5 times the mass of explosive α. Because of the direct proportionality between plate peak deflection and blast impulse, these results suggest that about 2.5 times the mass of explosive α is required, relative to explosive β, to deliver the same blast impulse to the witness plate.

Blast-induced plastic deformation of an aluminum panel

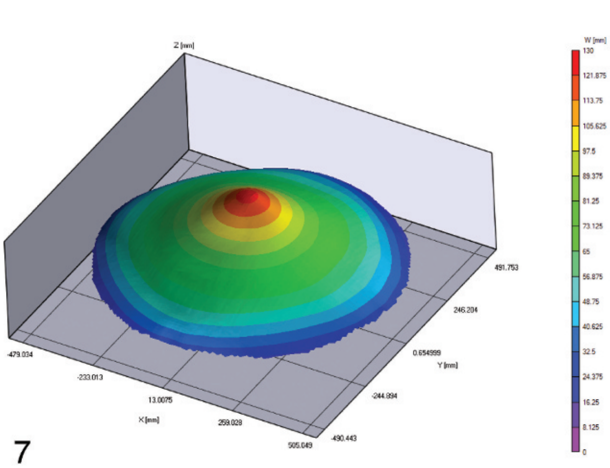
Image correlation was used to measure the blast-induced response of a 1/8 inch thick 6061-T6 aluminum panel due to detonation of a spherical charge of C-4 explosive. The panel was 122 cm (48 in.) square and bolted over a 107 cm (42 in.) diameter circular hole in a massive vertical steel bulkhead. The panel was clamped to the steel bulkhead on the blast side of the bulkhead by a square steel backing frame that enveloped the 107-cm panel working diameter. Hence the loaded area of the square panel was circular, but the panel was clamped over a square contour. The charge weight and the standoff distance between the charge and the panel center are here left unspecified for security reasons. Camera frame rate and image resolution were the same as in the measurements of witness plate deflection discussed in the previous section.

Figure 7 shows contours of the transverse deflection of the aluminum panel at peak deflection. This peak transverse deflection, of magnitude 125 mm, occurred at the panel center 21 images or 2.1 ms after the last photographic image without deformation. Therefore the average transverse velocity of the panel center from the initial undeformed condition to the peak deformation in *Figure 7* is about 60 m/s. The maximum velocity during the deformation process is actually far greater than this (see later discussion). The much larger velocities for the aluminum panel compared with the steel witness plate (~16 m/s), aside from variations in explosive type and standoff, are due to the much smaller mass of the aluminum panel.

Figure 8 shows contours of the in-plane displacement for the aluminum panel in the test described previously; however, *Figure 8* does not correspond to the image with peak transverse deflection as in *Figure 7*. Instead *Figure 8* corresponds to an earlier image that succeeds the last undeformed image by three images and precedes the image with maximum transverse deflection by 19 images. The contours in this plot correspond to in-plane displacement in the *X*-coordinate direction. This displacement, which is on the order of 1 mm, is denoted by U in *Figure 8*. The transverse displacement is also indicated in this figure, qualitatively, by the shape of the contour plot surface. Note that the transverse displacement is limited to the central area of the panel at this time. However, the in-plane displacement has spread well beyond the central region where transverse deformation has occurred. Note that the U (in-plane) displacement in the right half (positive *X*) of the deformed central region is positive whereas U in the region exterior to this on the same side of the panel is negative. This behavior is present on the left side of the panel as well. Although it is not shown, almost identical behavior is observed for the in-plane displacement in the *Y*-direction. These features of the in-plane displacement are consistent with radial motion in the outer region directed radially inward toward the central deformed region. In effect, the panel material is flowing radially inward toward the central region of the panel to sustain the transverse deformation that is occurring there. By inspection of consecutive images like *Figure 8* during the initial 100 μs of the deformation process, we found that the rate of radial spreading of the in-plane displacement must be in excess of 3,500 m/s. For reference, the propagation velocity of small amplitude longitudinal waves in aluminum (the velocity of sound) is 6,420 m/s.

Figure 9 shows profiles of transverse deflection on the 6061 aluminum panel over the panel diameter $Y = 0$ at various times during the deformation process. These data correspond to a similar test with a charge configuration different from the test depicted in *Figures 7 and 8*. Time zero for the test in *Figure 9* corresponds to the last undeformed image. Note that the transverse velocity is greatest very early in the process. Between the profiles corresponding to times 0.1 and 0.2 ms, the average transverse velocity at the center of the panel is 300 m/s. The transverse velocity reduces rapidly as the peak deflection of 150 mm is approached at 2.2 ms. The profile shapes in *Figure 9* indicate strong curvature near the center of the panel within a radius of about 100 mm from the panel center. This curvature remains relatively constant from about 0.2 ms to the peak deflection at 2.2 ms. Although later profiles are not shown in *Figure 9*, those later profiles, aside from some elastic oscillation, indicate very nearly the same shape and deflection magnitude shown in *Figure 9* at peak deflection. The absence of significant deflection rebound suggests that most of the panel deformation observed in the peak deflection profile is due to plastic strain.

Figure 10 shows the time histories of the transverse displacement and the first principal strain at the center of the aluminum panel corresponding to the deflection profiles plotted in *Figure 9*. The symbols correspond to individual image correlation measurements of deflection and strain at the panel center in each image.



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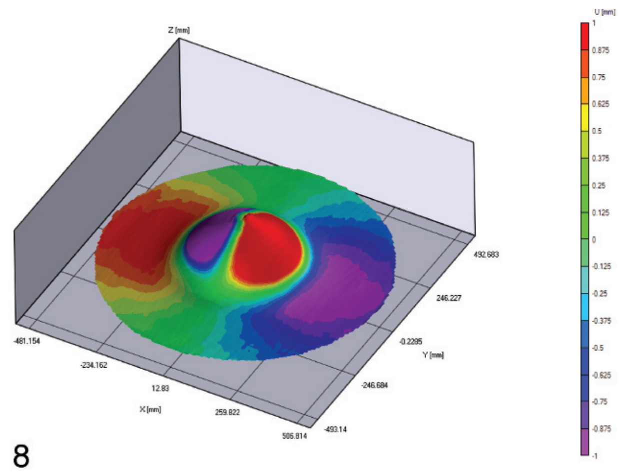

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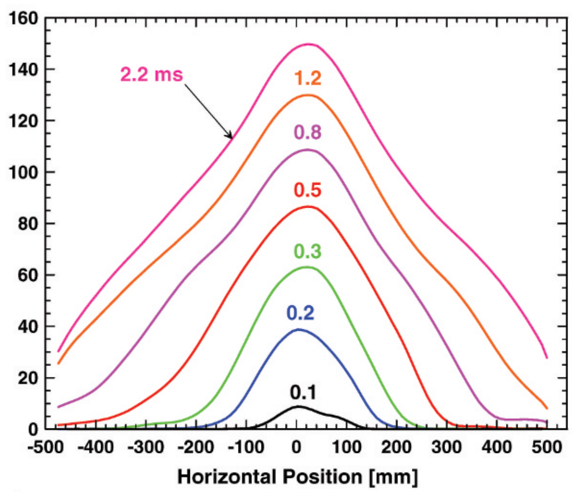

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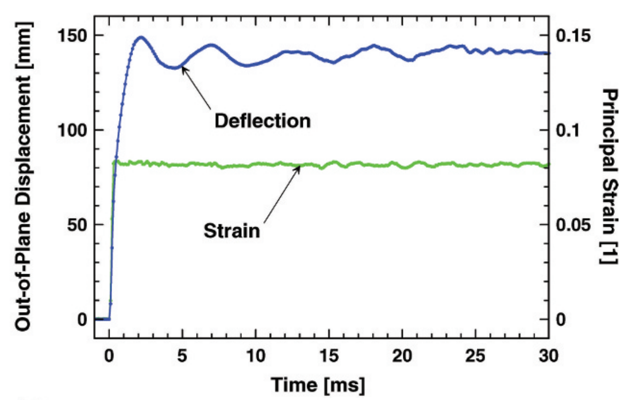

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Figure 7. Contours of transverse deflection: 6061-T6 aluminum panel (upper left). Figure 8. Contours of in-plane displacement: 6061-T6 aluminum panel (upper right). Figure 9. Deflection profiles: 6061-T6 aluminum panel (lower left). Figure 10. Deflection and strain history at center: 6061-T6 aluminum panel (lower right).

Except for some damped oscillations, the deflection magnitude changes relatively little after the peak deflection of 150 mm is reached at about 2.2 ms. The deflection history in *Figure 10* supports the conclusion reached on the basis of the deflection profiles in *Figure 9* that most of the initial deformation is plastic deformation. This conclusion is further supported by the strain history at the panel center, also plotted in *Figure 10*. Close examination of the strain variation in *Figure 10* indicates that the peak strain at the panel center is achieved only about three images or 300 μs after the first deformed image. After this time the strain is relatively constant at about 0.082 or 8.2%. Because this strain magnitude is far in excess of the yield strain of about 4,000 με for this 6061 alloy, the material at the center of the panel has clearly experienced large plastic deformation. This strain level, however, is well below the 17% elongation at rupture measured in quasi-static testing for 6061-T6 aluminum, cf. Lynch (1989).

Blast response of commercial aircraft fuselage skin

Image correlation measurements were made on the external skin of an unpressurized commercial aircraft during an internal blast. In this test a portion of the cargo hold was protected by a flexible panel of blast mitigation material that was attached to the inboard side of the airframe. The blast was due to a spherical explosive charge that was placed inside a suitcase filled with typical luggage contents. The suitcase was located in the cargo hold adjacent to the mitigation panel at a particular distance, to remain unspecified here, from the inboard surface of the panel. During the course of this test, the aircraft skin experienced significant radial deflection and permanent deformation in the neigh-

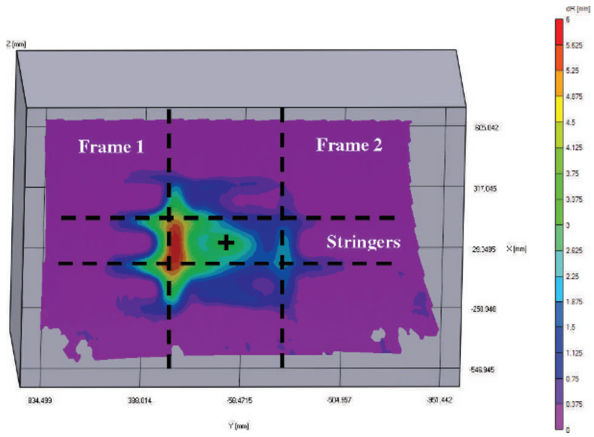

Figure 11. Contours of radial skin deflection: 0.56 ms.

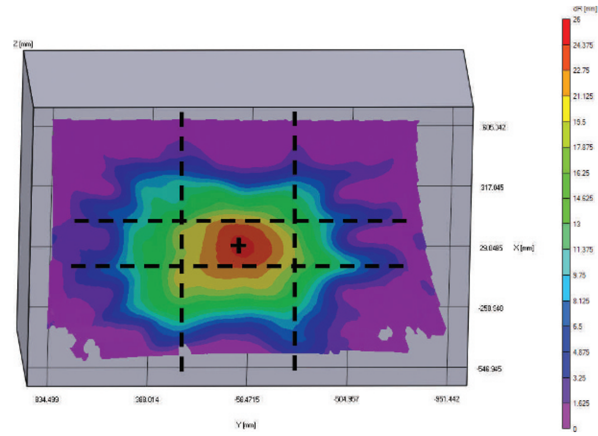

Figure 13. Contours of radial skin deflection: 1.56 ms.

borhood of the charge location, but it did not rupture. Because the skin failed completely in an identical test conducted without a blast mitigation panel, survival of the skin in the present test is attributed to the presence of the panel. The image correlation data presented later suggest some physical mechanisms that might have contributed to the successful mitigation of the blast.

The external skin of the aircraft cargo bay was speckle painted over the area protected by the blast mitigation panel. The high speed video cameras were focused on this section of the external skin, about 3 m (9.8 ft) from the skin and separated by approximately 1.5 m (5 ft). Photographic images of the blast-induced skin deformation were recorded using a frame rate of 9,000 fps and an image resolution of 640 × 480 pixels. This frame rate corresponds to 111 μs spacing between consecutive photographic images.

For image correlation analysis, deformation of the skin is measured with respect to a cylindrical coordinate system that is fitted to the undeformed skin surface by the image correlation software. The radial, axial (longitudinal), and circumferential displacements of the

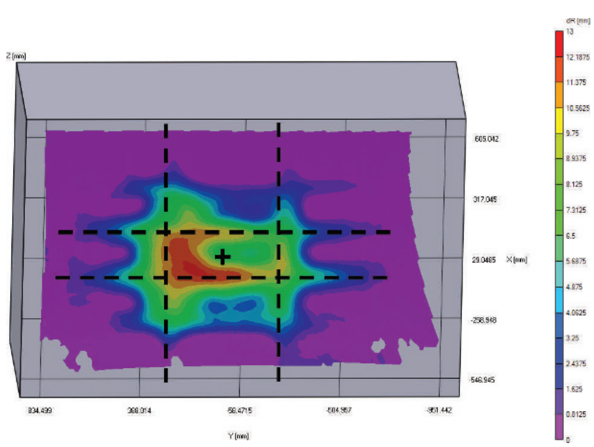

Figure 12. Contours of radial skin deflection: 1 ms.

skin are measured in this cylindrical coordinate system with respect to the position of the undeformed skin in the preblast condition. *Figures 11–13* show image correlation–measured contours of the fuselage skin radial deflection in the neighborhood of the charge location. In these plots the radial deflection is denoted by the symbol dR. The approximate locations of the charge and the frames and stringers adjacent to the charge are also shown in these figures. For reference the frames forward and aft of the charge location are denoted as frames 1 and 2, respectively. *Figure 11* shows the radial skin deflection five images or 0.56 ms after the first deformed image. In this plot the radial deflection is seen to be concentrated along frame 1 forward of the charge location and to a lesser extent longitudinally along the two adjacent stringers forward of the charge. The largest deflection is about 6 mm and occurs just aft of frame 1, cf. *Figure 11*. More modest radial deflection of the skin appears aft of the charge along frame 2. Some deflection is also observed at the stringers that lie above and below the stringers drawn adjacent to the charge. The correlation of the skin radial deflection pattern with the underlying airframe in the neighborhood of the charge suggests that a substantial portion of the blast load is being transferred by the mitigation panel to the skin through the airframe. *Figure 12* shows skin radial deflection contours four images or 0.44 ms after those depicted in *Figure 11* or 1 ms after the first appearance of skin deformation. At this time the skin radial deflection is concentrated mostly along circumferential and longitudinal directions coincident with the frames and stringers adjacent to the charge as in *Figure 11*; however, the skin deformation is now more symmetrically distributed forward and aft of the charge location. The peak radial deflection has increased to about 12.5 mm, and this peak deflection is located forward of and slightly below the charge. *Figure 13* shows contours of the skin deflection five images or 0.56 ms after the

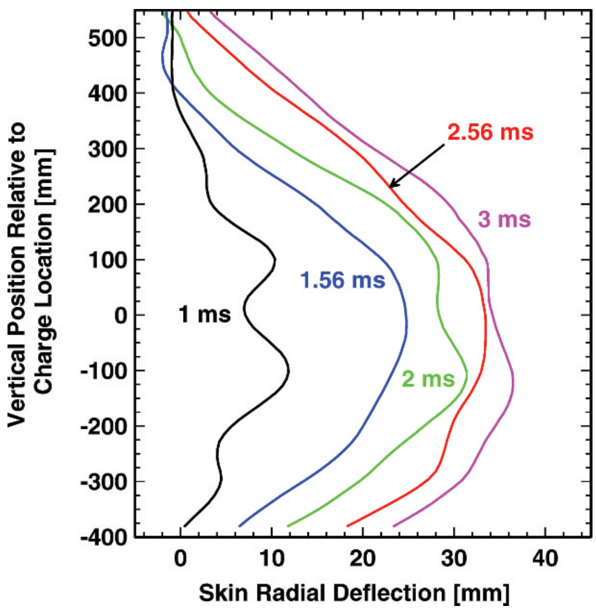

Figure 14. Profiles of radial skin deflection: Vertical contour through charge.

image in *Figure 12*. This plot indicates that the skin deformation is concentrated concentrically around the charge location with the peak deflection of about 25 mm occurring within a centimeter of the charge. The blast load continues to be transferred to the skin through the airframe; however, this transfer is now dominant only outside of the frame bay containing the charge. These skin deflection contour plots suggest at least one mechanism by which the mitigation panel reduces damage to the skin. Rather than allowing a highly impulsive and spatially concentrated load to act over a relatively small area of the skin, the panel causes the blast load to be distributed over a sizable portion of the frame and stringer system.

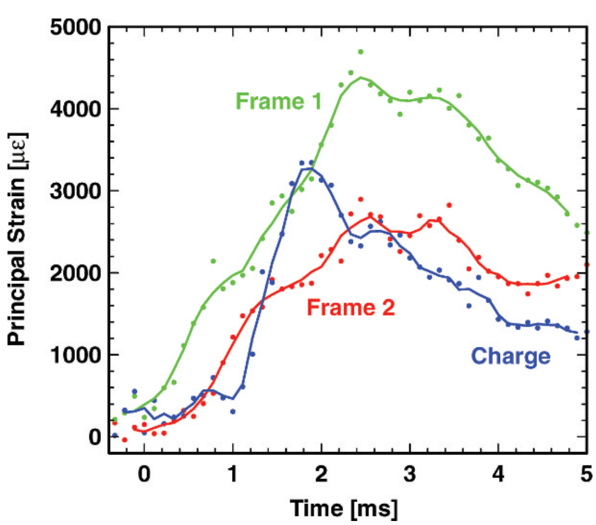

Figure 15. Time histories of principal strain in skin.

Profiles of the radial skin deflection are plotted in *Figure 14* for a vertical–circumferential contour passing through the charge location at various times from 1 to 3 ms after the first deformed image. The origin of the vertical coordinate on this graph corresponds to the charge location. The earliest profile, at 1 ms, shows the greatest influence of the two adjacent stringers on the skin deflection. These stringers are located at approximately ±100 mm in *Figure 14*. At this time the next closest pair of stringers to the charge is also seen to be applying modest load to the skin. The profiles for later times indicate a more uniform distribution of the deflection, which is more centered at the charge location and is consistent with the skin deflection contours in *Figures 11–13*.

Figure 15 shows the histories of the principal strains on the skin at the charge location and at the adjacent frames for the first 5 ms following the first deformed image. The measurements of the strain in the skin by image correlation for each image are shown as data points with temporal spacing of 111 μs. The substantial noise level in the strain results from the rather small in-plane displacement from which the strain is calculated. Because of this high noise level, smoothed (solid) curves have been plotted for each data set using a running average type of smoothing with a smoothing window width of five data points. The highest strain in the first millisecond occurs at frame 1 because of the strong initial deflection there; however, the strain at this frame continues to exceed the strains at the charge and at the aft frame (frame 2) throughout the first 5 ms of the event, cf. *Figure 15*. Peak strain at frame 1 is about 4,500 με occurring at approximately 2.5 ms. The peak strain of about 3,200 με at the charge location occurs slightly earlier at about 1.8 ms, and the peak strain at the aft frame (frame 2) is smaller still, cf. *Figure 15*. These strain peaks precede the peak radial deflection of the skin (~37 mm) at the charge that occurs around 5.5 ms. The skin strain levels indicated in *Figure 15* are near the yield strain for the 2024-T3 skin material (~4,700 με) so the skin may have experienced modest plastic deformation during the test.

Conclusions

Digital image correlation has been used to make full-field noncontact measurements of the blast-induced response of three different structures. These structures included a steel witness plate, a thin aluminum alloy panel, and the cargo bay area of a commercial aircraft fuselage that was protected by a blast mitigation panel. This measurement approach made it possible to study the time evolution of the deforming shape of these structural surfaces as well as the spatial distributions and time histories of transverse deflection, in-plane displacement, and strain. Measurements of witness plate peak deflection facilitated the determination of explosive equivalence for three different explosives in the sense of blast impulse. Correlation measurements for the blast response of the thin aluminum panel indicated a peak transverse deflection of 150 mm, peak panel velocity of 300 m/s, and large plastic strain in the blast-affected area exceeding 8%. Measurements of the skin deformation for an internal blast in the aircraft cargo bay suggested at least one mechanism by which the mitigation panel was able to prevent skin breach. Rather than allowing a highly impulsive and spatially concentrated load to act over a relatively small area of the skin, correlation measurements showed that the mitigation panel caused the blast load to be distributed over a sizable portion of the frame and stringer system. These results demonstrate that image correlation is an important technique for gathering critical structural response data during blast testing, which may be too severe or hazardous for other measurement approaches. ❑

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Capabilities in Context: Evaluating the Net-Centric Enterprise

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Traditional interoperability testing focuses on the operational effectiveness of preplanned information exchanges to and from the capability being tested as well as functionality of the capability to perform its mission objectives. As the Department of Defense continues to migrate to a net-centric architecture, standalone systems will be replaced with service-based capabilities deployed in various enterprises. In this context, a capability inherits both the risks and requirements associated with that enterprise. The relationship between a capability and the enterprise on which it is deployed is symbiotic and, as such, requires an evaluation of capability functionality as well as the ability of the enterprise to support the capability's mission-driven business processes.

Key words: Net-centric enterprise; enterprise-level test approach; information sharing; operational suitability; effectiveness; survivability; requirements; metrics.

The Department of Defense (DoD) test community has a long history of "program-level" interoperability testing. Current methods focus on assessing information exchanges for operational effectiveness, but do not include an assessment of the enterprise architecture components. The enterprise is a community of systems and services (e.g., people, organizations, and technology) that are interdependent and must coordinate functions and share information in support of a common mission or a set of related missions. This test philosophy cannot support a net-centric DoD where decision making is based on tiered accountability and federated governance. In the net-centric enterprise, the line between "mine" and "yours" no longer exists. Investments are still made based on capability gaps, but only after the benefits of reuse and loose coupling are fully exploited through the application of service-oriented architecture (SOA) best practices. The tester must look at the enterprise holistically and determine when it comes to net centricity, how are we doing?

Introduction

The Defense Information Enterprise Architecture (DIEA) v1.0 (April 2008) describes the DoD net-centric vision as follows[1]:

> *"To function as one unified DoD Enterprise, creating an information advantage for our people and mission partners by providing:*
>
> - *A rich information sharing environment in which data and services are visible, accessible, understandable, and trusted across the enterprise;*
> - *An available and protected network infrastructure (the Global Information Grid (GIG)) that enables responsive information-centric operations using dynamic and interoperable communications and computing capabilities."*

As testers, how do we ensure that the DoD does, in fact, operate as one seamless and interoperable enterprise, even while implementing a tiered accountability decision model and a federated governance structure?

JITC proposes a test approach *(Figure 1)* that includes all of the components of an enterprise that are required to ensure success. However, not all requirements in the test approach will apply to every enterprise. The test approach should therefore be tailored to meet the needs of each unique enterprise. This approach aligns with DIEA objectives, imple-

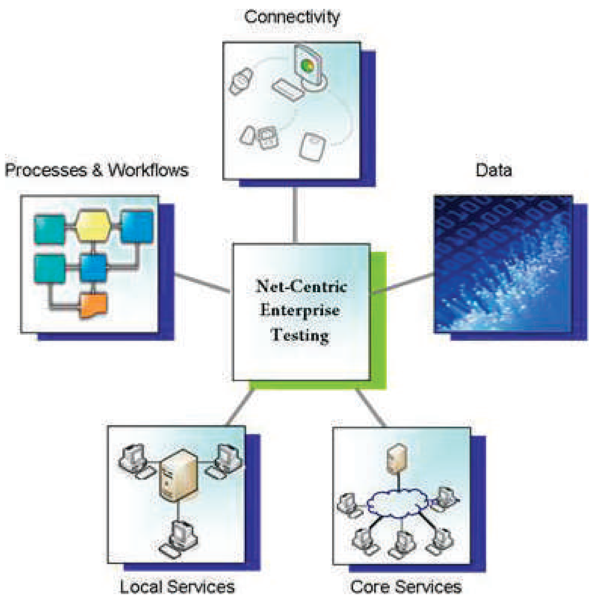

Figure 1. Net-centric enterprise testing approach.

ments best-of-breed practices from industry and academia, and provides value-added information to DoD capability portfolio managers, enterprise architects, and program managers for decision making. This approach provides technical rigor, flexibility, and scalability required to ensure testing provides value-added information within the cost and schedule constraints of rapid acquisition initiatives.

Connectivity

Connectivity refers to the hardware and software implementations that enable connection between clients and servers, between services, and among networks *(Figure 1)*. These implementations comprise the enterprise network infrastructure and support the mission-critical and mission-enabling (nonmission-critical) information exchanges between capabilities on the enterprise to include clients, servers, services, and networks.

Requirements

Compliance with the DIEA requires that the connectivity of the enterprise support capability missions by providing secure, dynamic, computing-platform agnostic and location-independent data storage, real-time provisioning, allocation of shared resources, and access to shared spaces and information assets within the mission-required Quality of Service (QoS) parameters.

Metrics

The following measurements comprise the suggested minimum set of metrics needed to support an enterprise connectivity assessment. However, this list should be tailored to accommodate each unique enterprise by either deleting nonapplicable metrics or adding new metrics.

Operational availability (A_o). Testers will review logs captured with an enterprise service management tool and verify the operational availability of the network connections. This is determined by using the operational availability equation [A_o = Mean Time between Failure (MTBF)/MTBF + Mean Time to Repair (MTTR)] and is represented as a percentage.[2]

Lowest throughput (in GB/s). This metric indicates availability of the network by measuring the lowest throughput speed at all nodes during normal message request load on the enterprise. A network experiencing lowered throughput may result in slow message exchanges that delay service access or interruptions in service access, which prevent function. Using a network loading tool, testers will simulate network load with a normal random distribution over time and measure the throughput speeds at all nodes. If the lowest throughput speed does not meet mission-critical threshold requirements, then the enterprise cannot support the mission.

Bandwidth usage. This metric indicates overall network load capacity. Bandwidth usage data are collected by enterprise service management tools and enterprise logs. The data traffic is then compared with the total data resources available. Testers will verify that the bandwidth used by the capabilities on the enterprise do not exceed the set limits defined in the foundational documentation. Measurements should focus on high traffic services and large data output services using realistic network load distributions over time.

Core Services

Core services are ubiquitous, common solution services that provide capabilities essential to the operation of the enterprise.[3] They are infrastructure-type capabilities that support multiple key consumers. Examples of core services include:

- security and authentication services,
- orchestration services,
- load monitoring services,
- load balancing services,
- messaging services,
- service configuration monitoring tools,
- enterprise service management tools,
- enterprise test tools,
- enterprise service bus capabilities.

Core service testing will target the core services that are available on the enterprise and will focus on their net-centric performance and design in support of capability mission requirements.

Requirements

Compliance with the DIEA requires that the core services deployed on a given enterprise support the mission by implementing a loosely coupled architecture that is visible, accessible, understandable, and trusted by both anticipated and unanticipated users. Core services must support mission requirements even during Disconnected, Intermittent, or Limited (DIL) bandwidth conditions and ought to provide Network Operations (NetOps) related data, such as performance and availability, to ensure compliance with GIG service level agreements (SLAs).

Metrics

The following measurements comprise the suggested minimum set of metrics needed to support an enterprise core services assessment. However, this list should be tailored to accommodate each unique enterprise by either deleting nonapplicable metrics or adding new ones.

Operational availability (A_o). Testers will review logs captured with an enterprise service management tool and verify the operational availability of enterprise core services. This is determined by using the operational availability equation (A_o = MTBF/MTBF + MTTR) and is represented as a percentage.[4]

Maximum latency (response time) for average request (in ms). Time difference between requestor's service request and service response (measured from time of service request [received at service provider] to time of response [sent from service provider]). Testers will test core service maximum latency to determine whether mission-critical threshold requirements for response times have been met.

Idempotency (in a stateless client). This metric indicates the uniformity of the responses from the core service. If the service client is stateless, then the response received after executing a service call should be the same no matter how many times the service call is executed.[5] Testers should send a statistically significant number of identical service calls (messages) to the core service and verify that identical responses are received.

Data accuracy. Core services that provide data should provide a quantifiable measurement of data accuracy. A capability could have varying degrees of accuracy requirements. Enterprise core services must, as a threshold requirement, support the highest level of mission-critical accuracy required by enterprise capabilities that will utilize those core services.

Maximum size of user domain. This metric indicates scalability of service, i.e., how well the core services can support the user domains required by the sum total of all missions executed in the enterprise.

Maximum number of simultaneous users. This metric identifies the maximum number of concurrent users performing "normal" operations beyond which A_o or throughput falls below acceptable levels. It indicates scalability of core service and consistency of performance under varying load conditions. The threshold requirement for each enterprise core service must represent the sum of the average number of concurrent users required by all supported capabilities deployed on the enterprise.

Local services

Local services are application-type capabilities that provide a function in support of an operational requirement or mission. Local services may vary from extremely small bits of capability (provides a map) to large capabilities drawn from service enabling a stove-piped legacy system.

Local service testing focuses on both the functionality of capabilities on the enterprise, as well as compliance with inherited enterprise requirements.

Requirements

Compliance with the DIEA requires that the local services deployed on a given enterprise support the mission by implementing a loosely coupled architecture that is visible, accessible, understandable, and trusted by both anticipated and unanticipated users. Local services must provide access to authoritative data assets, services, and applications, and be accessible to all authorized users except where limited by law, policy, security, classification, or operational necessity. Local services must support graceful degradation of capability and performance during DIL conditions and ought to provide NetOps related data, such as performance and availability, to ensure compliance with GIG SLAs.

Metrics

The following measurements comprise the suggested minimum set of metrics needed to support an enterprise local services assessment. However, this list should be tailored to accommodate each unique enterprise by either deleting nonapplicable metrics or adding new metrics.

Service visibility. Testers will ensure that local service is registered in the enterprise service registry and is "discoverable" with an intuitive keyword search using the enterprise's federated search capability.

Service accessibility. Testers will ensure that local service has written policy listing actions necessary to gain transparent machine-to-machine access to services via user level credentials, system level credentials, or trust relationships (e.g., SLAs). This includes users who are anticipated (i.e., known users with specific missions that have been granted access to the system), unanticipated (i.e., users without specifically defined missions who have been granted access to the system), and unauthorized users (i.e., users without access to the system). Policy must be registered in the service's submission package located in the DoD Metadata Registry, and policy must be enforced as written.

Service understandability. Testers will ensure that the local service Web Services Description Language correctly executes service operations and any community of interest (COI) or Enterprise mandated vocabularies and schemas are used and implemented correctly.

Service reuse. Existing enterprise services and end-user interfaces shall be used whenever possible, practical, and appropriate instead of recreating those assets.[6]

Functional requirements. Local services used by the warfighter or capability must provide functional capabilities as described in the U.S. Joint Forces Command–maintained Joint Common System Functions List (JCSFL). The JCSFL provides a common lexicon for system Command and Control (C2) functionality, including the traceability of Military Service C2 functions to their joint equivalent, for interoperability and comparative analyses. The JCSFL describes the C2 functionality of any platform, program of record, system, subsystem, component, or application that provides such functionality. The JCSFL also contains intelligence, surveillance, and reconnaisance functions and will be updated to include net-centric communications functionality, as determined by the net-centric Capability Portfolio Manager. Support functions, including those for maintenance, logistics, medical, personnel, training, etc., will be included in future revisions.[7]

Operational availability (A_o). Testers will review logs captured with an enterprise service management tool and verify the operational availability of local services to each client capability. This is determined by using the operational availability equation (A_o = MTBF/MTBF+MTTR) and is represented as a percentage.[8]

Maximum latency (response time) for average request (in ms). This metric is the time difference between requestor's service request and service response (measured from time of service request [received at service provider] to time of response [sent from service provider]). Testers will test local service maximum latency to determine whether mission-critical threshold requirements for response times have been met.

Data accuracy. Local services that provide data should provide a quantifiable measurement of data accuracy. Local services must, as a threshold requirement, support the highest level of mission-critical accuracy required by the client capability.

Maximum size of user domain. This metric indicates scalability of service, i.e., how well the local service can support the user domains required by the sum total of all missions executed in the enterprise.

Maximum number of simultaneous users. Identifies the maximum number of concurrent users performing "normal" operations beyond which A_o or throughput falls below acceptable levels. This metric indicates scalability of local service and consistency of performance under varying load conditions. The threshold requirement for the local service must represent the sum of the average number of concurrent users required by all supported capabilities deployed on the enterprise.

Graceful capability degradation. This metric identifies local service ability to implement graceful degradation capabilities as outlined by mission requirements. Mission requirements ought to specify capabilities required under varying levels of DIL bandwidth conditions. Testers should evaluate local services under conditions specified to ensure that threshold capability requirements are met.

Data

Data testing will target the data assets that are shared within the enterprise and will focus on the ability of those assets to support mission-critical threshold capability requirements. There are two types of data: content data and metadata.

Content data are data provided by a capability that provides information usable by other capabilities or users. Content data address the needs of the COIs and users or warfighters directly. A capability generally generates, transforms, stores, or consumes content data.

Metadata are data that describe the characteristics of the capability or data exposed on the enterprise. Metadata generally describe content data and/or services that are available for consumption, e.g., what standards the service or data asset follows, how to use the service or data asset (for machine-to-machine interface), and how to discover the service or data.

Requirements

Compliance with the DIEA requires that the data deployed on a given enterprise support the mission by being visible, accessible, understandable, and trusted by both anticipated and unanticipated users. Data should follow the syntax and semantics as defined by the associated community of interest and should be appropriately tagged using the enterprise standard for discovery metadata (DoD Discovery Metadata Specification).

Metrics

The following measurements comprise the suggested minimum set of metrics needed to support an enterprise data assessment. However, this list should be tailored to accommodate each unique enterprise by either deleting nonapplicable metrics or adding new metrics.

Data visibility. Testers will ensure that discovery metadata are registered in an Enterprise Catalog in accordance with DDMS, thus making it discoverable within the targeted enclave. Testers will ensure that data are "discoverable" with an intuitive keyword search using the enterprise's federated search capability.

Data accessibility. Testers will ensure that Federated Search results provide active link (e.g., Uniform Resource Locator) that points to the specified data asset within the targeted security enclave. Testers will ensure that the data provider has written policy listing actions necessary to gain transparent user access to the data via user level credentials, system level credentials, or trust relationships (e.g., Access Control List). This includes users who are anticipated (i.e., known users with specific missions that have been granted access to the system), unanticipated (i.e., users without specifically defined missions who have been granted access to the system), and unauthorized users (i.e., users without access to the system). Policy information must be registered in an *enterprise catalog*, include the steps by which a user may request access to the data, and be available within "2 clicks" from the active link provided by Federated Search.

Data understandability. Testers will ensure that data are navigable within the limitations of the interface, are labeled with meaningful labels, are conveyed effectively, and use commonly understood language that conforms to COI-approved vocabularies.

Semantic reuse. Semantic vocabularies shall reuse elements of the DoD Intelligence Community (IC)-Universal Core information exchange schema.[9]

Data reuse. Existing enterprise data shall be used whenever possible, practical, and appropriate, instead of recreating those assets.[10]

Data accuracy. Data should provide a quantifiable measurement of accuracy. Data that are provided as a service should maintain source level of accuracy in accordance with mission-critical threshold requirements.

Data refresh rate. Data must maintain a refresh rate that is compliant with the threshold mission requirements for the client capability.

Graceful degradation. Data must be accessible during DIL bandwidth conditions. Data redundancy should be made available through the use of local caching and data storage. Data should be appropriately tagged with "age" or "time of last refresh" information so that the user or warfighter is aware of the currency of the data for decision making purposes.

Processes and workflows

A *process* is a composition of one or more types of services that are capable of accomplishing a particular part of a mission objective *(Figure 1)*. For example, "perform capability A, translate the results, then perform capability B" is a *process*. A *workflow* is a specific composition of processes and services that will accomplish a mission objective. For example, "service A calls translation service AB, which calls service B" is a *workflow*.

Processes and workflows testing will target the business processes that combine to form workflows to accomplish capability mission objectives.

Requirements

Process and workflow requirements should be derived from joint mission threads developed by the user representative for a given capability. Mission threads should provide operational activities, tasks, and required performance characteristics needed to meet threshold mission-critical requirements. Mission threads will be decomposed into the materiel and nonmateriel solutions required to execute the thread. The processes and workflows required to execute a given mission are best represented using dynamic modeling techniques such as business process modeling notation.

Metrics

The following measurements comprise the suggested minimum set of metrics needed to support an enterprise processes and workflows assessment. However, this list should be tailored to accommodate each unique enterprise by either deleting nonapplicable metrics or adding new metrics.

Operational effectiveness. Operational effectiveness is the overall degree of mission accomplishment of a system when used by representative personnel in the environment planned or expected for operational employment of the system considering organization, doctrine, tactics, survivability, vulnerability, and threat. The evaluation of operational effectiveness is linked to mission accomplishment. The early planning for the evaluation should consider any special test requirements, such as the need for large test areas or ranges or supporting forces, requirements for threat systems or simulators, new instrumentation, or other unique support requirements.

Operational suitability. Operational suitability is the degree to which a system can be satisfactorily placed in field use, with consideration given to reliability, availability, compatibility, transportability, interoperability, wartime usage rates, maintainability, safety, human factors, manpower supportability, logistics supportability, documentation, training requirements, and natural environmental effects and impacts. Early planning for the suitability evaluation should include any special needs for number of operating hours, environmental testing, maintenance demonstrations, testing profiles, usability of developmental testing data, or other unique test requirements. Operational suitability should be evaluated in a mission context to provide meaningful results. For example, maintaining a required Operations Tempo over an extended period while conducting realistic missions gives insight into the interactions of various suitability factors, such as the ability to maintain stealth features during sustained operations.

Operational survivability. Operational survivability is the degree to which a capability is able to resist or recover from detrimental effects. Measurement time frames should be from the start of unavailability to the time when service is restored. The enterprise should have automated tools in place to restore service automatically after service is lost.

Summary

This enterprise-level test approach provides the basis for evaluating a net-centric enterprise by examining the individual capabilities in context with the components of their parent enterprise: connectivity, core services, local services, data, and processes and workflows.

"Program-level" interoperability testing does not reveal problems that will occur as a result of the growing intricacy of client–service dependencies, changing interface requirements, and resource scaling issues as the enterprise (and its resident service, data and infrastructure assets) matures and multiplies. "Program-level" interoperability testing also does not reveal the benefits of reuse and loose coupling that may be achieved by the enterprise through the application of SOA best practices.

In contrast, this enterprise-level test approach will expose interservice dependencies and shortcomings and highlight the benefits of existing enterprise infrastructure and SOA governance assets that promote efficiency, enable development, and manage growth of net-centric technologies. ❑

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Laying the Foundations for True Cross-Domain Commonality: Why Is the Common Range Integrated Instrumentation System (CRIIS) Not the Answer for Test and Training Time-Space-Position Information?

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The vision of advancing to interdependent, interoperable, and, ultimately, common instrumentation for test and training has long been accepted as the utopian solution for accomplishing these two vital functions of defense preparedness. Whereas common challenges such as shrinking budgets, range encroachment, and diminishing frequency allocation would seem to compel these closely related domains to work together, cultural—not technological—barriers have prevented the U.S. Department of Defense from realizing this collaborative vision. The Test Resource Management Center, through its Central Test and Evaluation Investment Program, has initiated a standards-based approach to ensure that both the test and training communities have a common range platform from which to deliver time-space-position information (TSPI) suitable for both domains. The Common Range Integrated Instrumentation System (CRIIS) builds on the historical business model for common test and training range instrumentation, finally ensuring that the Department has a wholly government-owned solution ready to bridge the test and training interoperability gap. After years of closely analyzing the similarities of test and training TSPI systems, CRIIS contains all the right ingredients to deliver the most fundamental range capability using a common architecture…so why is it not the answer to both test and training domains?

Key words: Commonality; instrumentation; investment; range capability; test and training.

"If ever we are to achieve common test and training instrumentation, the time is now." For the past 20 years, countless studies, meetings, discussions, symposia, and papers have highlighted the benefits of achieving common test and training instrumentation. Numerous observers have cited that the most basic task of range instrumentation—providing time-space-position information (TSPI) on scenario participants—is so similar in both test and training domains that it would appear the obvious choice for a common solution. Discussions on the idea of interoperability—finding ways to share data among diverse systems—inevitably lead to the question, "Why do we have unique systems for each community?" Although the term "interdependence" has been used lately to describe the relationship between test and training systems, it neglects to address the obvious similarities between test and training TSPI systems that point to a shared solution. Commonality offers economies of scale that, alone, are worth the price of admission. The economic benefits address the primary fiscal challenges of both domains. For trainers, the test community offers a deeper investment pool for research and development (R&D) dollars; for testers, the training community brings an exponentially larger number of users to ensure production and sustainment beyond that which the test community alone could support.

But the real goals of common test and training systems transcend the economic benefits. Our world has progressed from an Industrial Age to an Information Age. Information technology is in many ways defining our generation. Warfighting has always evolved with the technological advances of the time, and this era is no exception. Information age warfare is characterized by the principle tenets of net-centricity, which exploits the key enabling functions of information technology and network technology, applied to the science of warfare. Four fundamental aspects of information/network technology must be considered in order to apply the technology in the most effective and efficient manner. First, the utility and effectiveness of information-enabled systems that work together to perform a collective task increase exponentially when connected over a common network. Second, these systems must be designed, tested, and operated as a networked System-of-Systems in light of the collective tasks. Third, networking systems and people together generally produces new capabilities that were impossible when the systems stood alone and requires modified operating approaches. Therefore, evaluating the performance of (testing) and operating (training) the System-of-Systems cannot be performed in a segregated manner. Fourth, no other technology moves at the pace of information/network technology. The serial approach to requirements validation (design, test, train, deliver) has proven inadequate, generally resulting in the delivery of obsolete capability that is not optimized for the joint net-centric battlespace.

What does this mean for the test and training domains? Both must accept that individual systems can no longer operate in isolation; that the measures for System-of-Systems performance are characterized as mission effectiveness, assessing information exchange end-to-end across mission threads; that the System-of-Systems includes equipment, people, and tactics, techniques, and procedures; that synchronized testing and training is required to optimize the rapid delivery of mission solutions; that synchronized testing and training requires a high degree of commonality in battlespace environments, infrastructure, and instrumentation; and, finally, that a partnership between the testers and trainers is the only way to achieve our collective objectives. Therefore, in addition to the fiscal advantages, the primary goals of common test and training are maximization of mission effectiveness through the application of net-centric technology and acceleration of the delivery of the ensuing warfighting capabilities with an agility that paces modern warfare.

In response, the acquisition community has identified net-readiness as a key performance parameter of every new major weapon system acquisition, leaving behind the era of stand-alone weapon systems testing. New weapons are designed at program initiation to function as a node in the joint net-centric battlespace, operating in most cases as both an information producer and an information consumer. These weapons rely upon a variety of off-board information sources, including command and control, sensors, and intelligence systems; these systems are fed through multiple information communication paths, chief of which is the Global Information Grid.

A weapon system unable to draw from and take advantage of the information-rich environment in which it will operate is critically handicapped. In recognition thereof, the Test Resource Management Center–led Joint Mission Environment Test Capability is laying the infrastructure to connect live, virtual, and constructive test participants from across the country and around the world. This construct aligns the test community with the U.S. Joint Forces Command Joint National Training Capability. With Joint National Training Capability, trainers already have begun to leverage live, virtual, and constructive capabilities at locations around the world to simultaneously enable more realistic training and avoid the expense and delays associated with transportation of all participants to a single geographic location. Consequently, a major opportunity has emerged for test and training interdependence, interoperability, and commonality. Testers can tap into this opportunity to render operational testing more realistic through traditional training venues, such as the red and blue flag exercises, while continuing to collect evaluation-quality weapon system data. Similarly, trainers can create scenarios to engage the most realistic threats available on traditional test ranges, creating a target-rich environment for warfighters to assess and hone tactics, techniques, and procedures.

The avenues for common exploitation of test and training resources are abundant. Two recent memoranda, jointly signed by leadership within the offices of the Director, Operational Test and Evaluation; Under Secretary Defense for Personnel and Readiness; and Under Secretary of Defense for Acquisition, Technology and Logistics noted the need for interdependent test and training capabilities, beginning with airborne instrumentation.

It is evident that today no insurmountable technical barriers exist to prevent interoperable, or even common, test and training systems. To better appreciate the issue in modern context, we will present a historical overview. Then, we will explore the technological arguments against commonality, demonstrating why they are largely overstated and how they can be resolved with current state-of-the-art technology. Finally, we will make a close examination of the Common Range Integrated Instrumentation System (CRIIS), illustrating how the standards-based approach greatly reduces any technological barriers that may have existed previously. The time for highly interoperable systems is here. If not us, who? If not now, when?

A historical perspective on TSPI: Are we condemned to repeat the past?

Ironically, to a large extent the airborne TSPI business began on common test and training footing. Tracking fast-moving targets across vast range space required a function called range control, keeping all participants where they needed to be for safety and evaluation purposes. The common solution for test and training was instrumentation radars, which still have utility for both communities today. However, one of the many drawbacks of radar is that accuracy degrades rapidly as a function of distance. To address radar deficiencies, a new tracking scheme, multilateration, was born. Two-way ranging signals from a number of survey-in fixed sites are used to provide accurate TSPI on range participants.

At this point test and training systems began to diverge. Multilateration systems are often terrain-dependent, driving them to different configurations, frequencies, power levels, etc. Then, in the early 1980s, researchers began to examine the application of a new technology to range-independent TSPI for air, land, and sea participants. This new technology, a space-borne multilateration system, while still in its infancy was dubbed the Global Positioning System (GPS). In 1985, the Office of the Secretary of Defense initiated the Advanced Range Data System (ARDS) program to develop GPS-based TSPI instrumentation for national test ranges. This instrumentation consists of a high-dynamic GPS set for aircraft and a low-dynamic GPS set for ships, land vehicles, and slow-flying aircraft (e.g., helicopters). The high-dynamic instrumentation was provided in two packages: an internal mount configuration and the more widely used "pod" configuration. Because this was applied primarily to U.S. fighter jets, a common pod interface based on the AIM-9 missile was used. The instrumentation package consisted of five key components: a GPS engine, an Inertial Measurement Unit (IMU), a two-way datalink, an onboard recorder, and an encryption system. GPS technology had rekindled the possibility of common test and training instrumentation—it nearly happened.

The original ARDS was developed by Interstate Electronics Corporation. In the mid-1990s, Metric Systems (now part of DRS Training and Control Systems) won the production contract, producing approximately 300 participant packages for the test ranges. Metric recognized an opportunity to market this capability in the training market and, subsequently, won a contract to provide the U.S. Air Forces in Europe Rangeless Instrumentation Training System (URITS), which enabled training missions to be conducted from Air Force bases in Europe where fixed ground infrastructures for range support were not readily available. Although not interoperable, the similarities between URITS and ARDS and the potential for interoperability are astounding; essentially, the systems are very similar except for some software modifications, the radio frequency front end, and the ground processing. Metric, however, did not stop there. At least two other systems, the P4 Refurbishment Contract system and the airborne segment of the Cubic Defense Applications' P5 Combat Training System (P5CTS), also are direct derivatives of ARDS. Today, P5CTS has become the mainstay training TSPI system in the Department of Defense. Because of a common architecture, the technologies incorporated in these products have been inserted back into the ARDS system as well; the latest version offers improved performance, maximizes commonality with training products, and includes foreign military sales and training variants.

This history lesson proves that test technology can be used by the training community. In the past, differences between training and testing equipment were driven by the need for greater precision in testing and the reluctance of the training community to pay for that precision. Advances in technology employed in ARDS and P5CTS pods demonstrate that the cost of precision has become affordable and that standardization between test and training equipment architecture results in savings for both production and logistics.

It is important to note that had the government predicted the success of ARDS for both test and training applications it easily could have synergized design properties to provide a *common* system to support either test or training with minimal hardware differences, making seamless test and training possible while significantly reducing R&D investment and life cycle support costs.

In light of this information we need to ask, "What can we in government leadership do differently now?" and "How can we keep history from repeating itself?" But first we talk about the technology.

Test and training are technologically very similar

The world of instrumentation has changed dramatically during the last 10 years. GPS has become the core technology for TSPI applications, and other technology advancements have resulted in more-capable, lower-cost instruments. These advances include inexpensive, high capacity recorders; fast, inexpensive, small microprocessors; and high-performance, miniaturized inertial measurement units. Additionally, the reduction in usable radio frequency spectrum has necessitated the ability to conduct test and training missions with advanced state-of-the-art, spectrally-efficient datalinks. Consequently, test and training instrumentation systems now are amazingly similar. Functionally, both employ a two-way datalink, a GPS/IMU TSPI system, an encryptor, a high capacity recorder, and one or two microprocessors. In fact, as previously mentioned, the P5CTS datalink actually is a derivative of the ARDS datalink developed by the test community. This begs the question, "Then why are the two systems not the same?" They should be.

Both communities are likely to use the same onboard GPS and IMU hardware. Performance enhancement is achieved by employing a network of ground-based reference receivers and software modifications to accept differential corrections (via the datalink) and using Kinematic-like software algorithms. The key point is that the added performance demanded by testers is achieved with minimal, if any, cost impact on airborne instrumentation; hence, there would be no cost impact on trainers if they did not desire higher accuracy. It should be noted, however, that no-drop bomb scoring and missile fly-out simulations could benefit from higher accuracy TSPI.

Both communities need state-of-the-art embedded processing resources. It is clear that if ever commonality is to occur, sufficient processing horsepower must be made available to support both domains. Ten years ago, this may have been a true technological barrier; however, with the advent of unprecedented, affordable processing capabilities in smaller packages, and the need for operationally realistic, net-centric operational events, *both domains are faced with increased processing needs that can be met with common embedded processing*.

Both communities see multiple levels of security as essential to their TSPI instrumentation needs. Given the drive for greater coalition-based warfare and related exercises, trainers have pointed to the need for some form of multilevel security. Net-centricity demands that testers also evaluate systems in a coalition warfare-based environment, again supporting *a common multilevel security architecture*. (Based on current technology, it is becoming increasingly evident that achievable multilevel security lies in the Multiple Independent Levels of Security architecture, in which independent participants process all data at their personal level of encryption, while data blending is created via post-processing using a cross-domain solution to share data at appropriate classification levels.)

Both communities require similar datalink properties, especially regarding operational range, flexibility, and reprogrammability. Testers and trainers both employ a two-way datalink that operates in the L-band (1–2 GHz); the primary purpose of these datalinks is to pass TSPI data. Moreover, both communities are developing Joint Tactical Radio System (JTRS)–compliant waveforms, the training version of which is referred to as the Range Instrumentation Waveform (RIW). It is true that testing and training operate at different frequencies in the L-band and that the new waveforms will employ different access schemes. Typically, periodic messaging for testers will be implemented with time-slotted network access schemes, referred to as time division multiple access, whereas a periodic messaging for trainers will be implemented with signal collision avoidance network access schemes. *Nevertheless, with today's technology, it is straightforward to either:*

- *Build a radio that operates over both test and training radio bands and supports software versions of both community waveforms, or*
- *Develop a waveform that supports the needs of both communities.*

Given that requirements of testers and trainers can be met with very similar technologies, is there a system that can meet the needs of both communities?

The answer is yes.

CRIIS: A standards-based approach capable of meeting the requirements for both test and training

The Test Resource Management Center is funding the next generation GPS-based TSPI system, referred to as CRIIS, which incorporates a standards-based approach in the development of the system architecture *(Figure 1)*. This approach is being used in a number of areas, including incorporation of Test and Training Enabling Architecture (TENA) interfaces and the development of a JTRS-compliant radio. Internal standards are being developed to implement a modular, open architecture design, with Multiple Independent Levels of Security as an essential architectural element. Moreover, components will be miniaturized to help facilitate the placement of instrumentation inside space-limited vehicles.

CRIIS capabilities trace back to requirements developed and honed by the test community during the last 20 years and incorporated in the CRIIS Test Capabilities Requirement Document. In addition to meeting the needs of testers, the CRIIS Program Office has worked with training community representatives to compare, line-by-line, the P5CTS Operational Requirements Document and the CRIIS Test Capabilities Requirement Document to ensure that the CRIIS design can accommodate the needs of the training community. Not surprisingly, the result is that

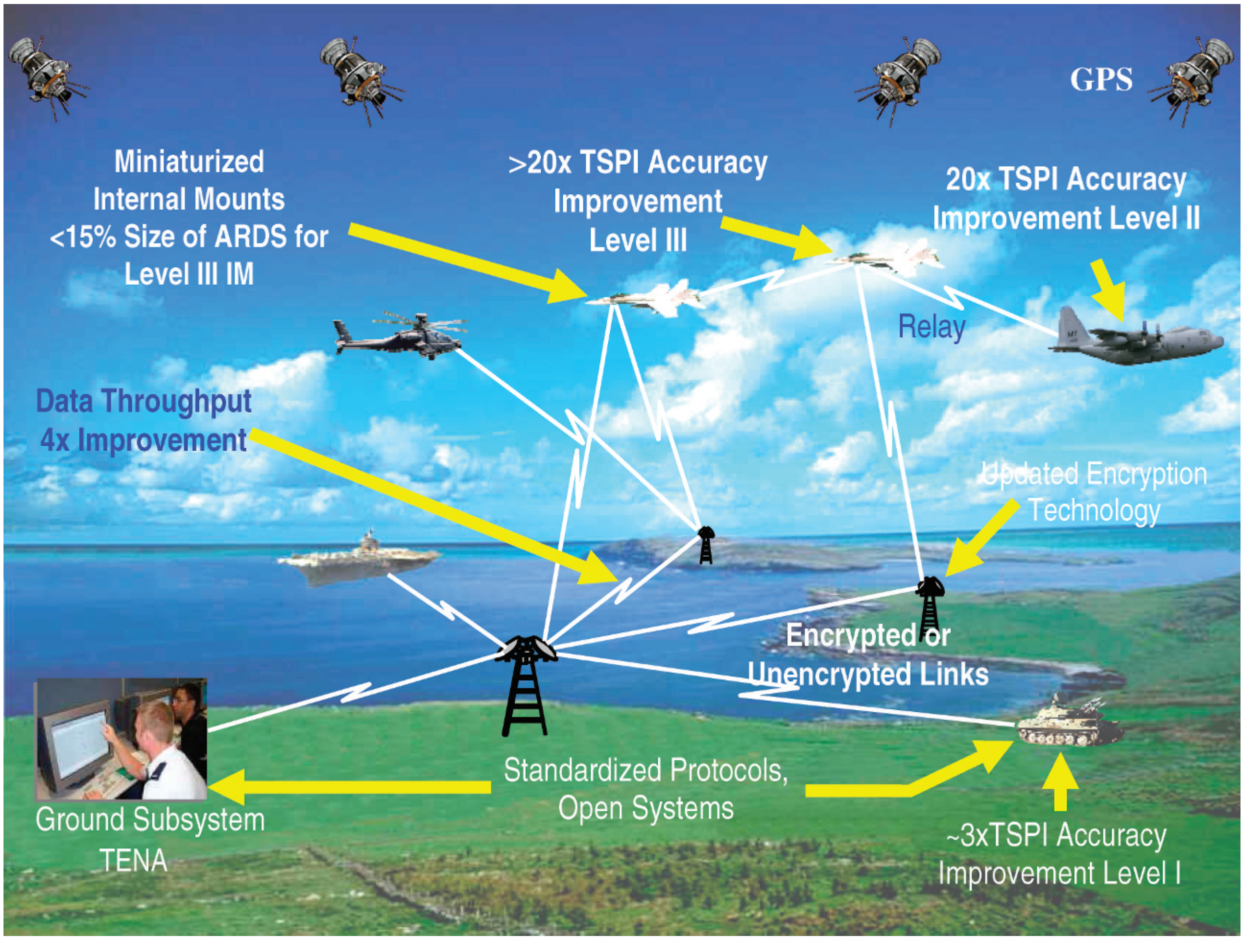

Figure 1. CRIIS Concept of Operations.

all but a few requirements are common to both communities; those that are not common can easily be engineered into the system for domain-unique application.

The major features of CRIIS include the following:

- A 20-fold improvement in TSPI accuracy by employing kinematic-type processing; the resultant submeter-accuracy will ensure that CRIIS remains a valid truth source for many years to come.
- A fourfold enhancement in datalink throughput; this is required to support a greater number of test participants, higher update rates, and greater accuracy.
- A radio compliant with software communications architecture that will employ spectrum efficient modulation; the software communications architecture will facilitate running other JTRS-compliant waveforms, such as RIW.
- A Multiple Independent Levels of Security–based radio that greatly simplifies the ability to conduct joint test or training exercises with our allies.

CRIIS will use TENA, the fundamental data-sharing medium adopted by both test and training communities and the cornerstone of the Joint Mission Environment Test Capability. Moreover, TENA is used by the training community and by several advanced instrumentation systems being developed by the Central Test and Evaluation Investment Program, including Integrated Network Enhanced Telemetry (iNET), Interoperability Test and Evaluation Capability, and the Joint Mobile Infrared Counter Measure Test System. By using TENA for all transmission control protocol/Internet protocol data transfer, CRIIS can be integrated into existing ranges and will be able to interoperate with other TENA-compliant systems, simulations, and hardware-in-the-loop laboratories. All existing TENA-compliant range control and display systems will be able to incorporate CRIIS with minor (if any) software modifications. The use of TENA makes the deployment of CRIIS to test and training ranges much more affordable than the deployment of ARDS was in the late 1980s and early 1990s.

The CRIIS radio will comply with applicable JTRS tenets, including adherence to software communica-

Table 1. Test and training requirements addressed by CRIIS capabilities

Required capability	Tester requirement	Trainer requirement	CRIIS capability
GPS/IMU-based TSPI	High accuracy	Moderate accuracy	Meets need of both communities with no added cost to trainers
MLS	Required	Required	MILS provided
Recorders	Moderate capacity	High capacity	Provides high capacity recorder with no added cost to testers
Microprocessors	Capacity/speed driven by TSPI	Capacity/speed driven by on-board weapon simulations	Microprocessors sized to meet the needs of both communities
Two-way Datalink	-Periodic messaging -Mid L-band -JTRS waveform	-Aperiodic messaging -High L-band -JTRS waveform	JTRS compliant radio with tunable RF front-end meets needs of both communities

CRIIS, Common Range Integrated Instrumentation System; GPS/IMU, Global Positioning System/Inertial Measurement Unit; TSPI, time-space-position information; MILS, Multiple Independent Levels of Security; JTRS, Joint Tactical Radio System, RF, radio frequency.

tions architecture design requirements and incorporation of JTRS Application Programming Interfaces. The primary impetus behind this design is the desire to provide a standards-based radio that can host RIW, which originally was intended to be hosted on the JTRS Small Form Factor-K radio. Because RIW will be a training range standard for some time to come and because of the desire to support joint test and training operations, the CRIIS radio will, as a minimum, implement all Application Programming Interfaces required to run RIW. Additionally, as the CRIIS test waveform is being developed, all JTRS Application Programming Interfaces will be implemented to the extent that they are technically feasible. The resulting radio will be submitted to the JTRS Joint Program Executive Office for inclusion in the JTRS library.

Clearly, this standards-based approach, employing state-of-the-art technologies, provides a common system that can readily meet the requirements of both the test and training communities *(Table 1)*.

Cultural versus technological barriers

Because there are no insurmountable technological barriers to creating common test and training instrumentation, one inevitably questions why it does not yet exist. Here, we shift our focus to cultural differences in the test and training communities, exploring some of the key differences.

Range independence

Historically, testers envision large land- or sea-based ranges with fixed infrastructures to perform testing, whereas trainers migrate toward rangeless capabilities to facilitate training at any worldwide location. This cultural difference is sometimes used to justify different developments. The reality of this changing age is that weapons, such as small-diameter bombs, demand increased footprints beyond traditional range space; compound this with future platforms such as hypersonic vehicles and unmanned aerial vehicles and add the complexities of worldwide-distributed live, virtual, and constructive test and training, and it is evident that trainers are correct not to rely solely on traditional fixed ranges to solve future training challenges. Any new range TSPI system must support in-range and rangeless applications.

Philosophies of data link management

Some have argued that the need for aperiodic, rather than periodic, updates drives either domain to different data link architectures, in the process forever dividing the two domains; however, as we have shown, the differences are vastly overstated and can be technologically bridged within the state-of-the-art. Trainers are using the ARDS-based time division multiple access structure now and likely will continue to do so for the foreseeable future. Given enough throughput, the choke points of throughput necessary for engagement evaluations are tremendously reduced. Meanwhile, for testers in the closely related field of telemetry, work is underway on iNET, which seeks to provide the next generation of telemetry to test ranges. By adopting an Internet protocol-based approach to data collection, iNET has shifted away from absolute periodic test data, opening the door to testers living with some degree of aperiodic system-under-test updates. Thus, iNET provides the flexibility both for periodic messaging schemes (as with URITS and other current training systems) and for aperiodic messaging (as testers will with iNET). Even if both communities insist on maintaining their community-unique messaging scheme, it would not be a showstopper for achieving highly interoperable systems; conceivably, a single test and training waveform could be developed to support both communities (e.g., two modes of which half the time is devoted to periodic messaging and the other half to aperiodic messaging).

Obsolescent-driven investment

Both test and training domains are reticent to provide wholesale overhauls of their respective TSPI infrastructures, historically waiting until the brink of obsolescence to change. When this change becomes inevitable, there can be apprehension that Service leaders might delay needed production efforts to wait for the next promised technological innovation. Trainers presently completing acquisition of the P5CTS system have breathing room to consider making a technological change to an upgraded capability, whereas testers must replace the near-obsolete ARDS system with CRIIS in the near future. Thus we find ourselves in a unique situation where collaborative investment by both domains is both attainable and sensible.

Fixed philosophies, changing realities

A common mantra heard among trainers is, "If we do not need enhanced accuracy, why pay for something we do not need?" As previously discussed, the enhanced accuracy provided by CRIIS comes at *no cost* to trainers if they do not need it. The reality, though, is that every time positional accuracy improves, testers and trainers find ways to exploit it—for better weapons, better test results, and better training. Moreover, a standards-based approach enables testers to adapt individual systems for higher accuracy without requiring fleet-wide fixed investments by all users, potentially including trainers. Testers historically have envisioned isolating a single system for evaluation; however, net-centricity has made that way of thinking obsolete. Once more a common solution is both logical and readily achievable. The nexus between test and training has never been greater nor a common solution more evident.

Ideal solutions versus real budgets

Finally, any discussion of commonality for test and training systems is incomplete without consideration of fiscal realities. There is a cultural tendency for trainers to ride the bow wave of R&D investments by communities with deeper technology investment dollars. Historically though weapons R&D has yielded few turn-key solutions for either the test or training community; significant development remains to adapt weapon technology to test or training. In reality the best source of R&D for the training community has been, and continues to be, the test community.

The principle challenge of pooling R&D investment dollars for common solutions has long dogged both test and training communities. The former, though, have a decided advantage in the Central Test and Evaluation Investment Program and the Test and Evaluation/Science and Technology Program, which provide approximately $250M annually for multi-Service–related investments across the test domain; no equivalent programs exist within the training community. One solution could be the creation of a single, unified investment house to address both test and training domains across the Services, with enough investment resources to address both communities effectively and efficiently.

Summary: The time for test and training commonality is now!

The bottom line is that *no* technological hindrances are preventing the test and training communities from employing common TSPI instrumentation, and cultural differences have been mitigated with blended test and training approaches. CRIIS represents a unique opportunity to provide the most basic test and training function, TSPI, on a common platform and, in turn, to realize significant benefits for both domains.

The time to act is now! The increased benefits are evident, and a detailed cost benefit analysis conducted by the Air Force revealed a potential for an annualized savings of $14M per year across both test and training domains if we migrate to a common test and training TSPI platform. However, CRIIS will soon enter system development, and once that occurs the window of opportunity for maximum commonality will be lost. *The testing community strongly encourages our training brethren to join the CRIIS effort now.* ❑

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Results of Distributed Tests With Integrated Live-Virtual-Constructive Elements: The Road to Testing in a Joint Environment

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The phrase "testing in a joint environment" refers to testing military weapons and supporting systems in the joint mission environments in which those weapons and systems are expected to operate. The Office of the Secretary of Defense chartered the Joint Test and Evaluation Methodology project to institutionalize testing in a joint environment by improving the ability to conduct tests, across the acquisition life cycle, in realistic joint mission environments. Specifically, the project was directed to develop methods and processes for using distributed live-virtual-constructive joint test environments to evaluate system performance and joint mission effectiveness. In 2007, the project completed a series of such tests to assess an initial set of methods and processes. Tests of network-enabled air-to-surface weapons and ground-launched surface-to-surface precision attack missiles were used to provide context for system performance evaluations. Joint mission effectiveness was evaluated by conducting Joint Fires and Joint Close Air Support with the above weapons and other supporting systems. These tests were accomplished as part of the 2007 INTEGRAL FIRE event sponsored by the Air Force Integrated Collaborative Environment program. This article describes results after methods and processes for testing in a joint environment were used by experienced testers to design and assemble an actual distributed joint test environment. Results identified improvements to the processes as well as recommendations for test organizations. To streamline routine test planning for distributed testing, we recommend test organizations consider procedures such that each acquisition program has a lead test organization designated for distributed testing. We also recommend that test organizations consider establishing formal relationships to manage the distributed test environment as a single facility.

Key words: Testing in a joint environment; distributed testing; live-virtual-constructive; LVC; joint test environment.

The Joint Test and Evaluation Methodology (JTEM) project was chartered to investigate, evaluate, and make recommendations to improve the ability to test across the acquisition life cycle in realistic joint mission environments. Specifically, JTEM was charged with developing, testing, and evaluating methods and processes for defining and using a distributed Live, Virtual, and Constructive (LVC) joint test environment to evaluate system performance and joint mission effectiveness. JTEM's initial set of methods and processes were developed in 2006. In 2007, the INTEGRAL FIRE test event was used to evaluate those methods and processes, which were used to plan and conduct tests of two systems as participating elements in an overarching system of systems. In this article, we describe those tests and how JTEM methods and processes were used to plan and execute them. The section "Testing in a joint environment" provides some background information on the vision within the

Department of Defense for improved testing in defense acquisition, including the notion of testing in a joint environment and the genesis of the JTEM project. The section "Methods and processes for testing in a joint environment" describes the specific methods and processes used during INTEGRAL FIRE planning and execution. Sections "Applying the methods and processes" and "Results and discussion" explain system performance and joint mission effectiveness tests resulting from the application of JTEM's methods and processes. The "Results and discussion" section explains the ability to evaluate the results of the systems performance and joint mission effectiveness tests as an indication of the effectiveness and suitability of JTEM's methods and processes. The final section summarizes our conclusions and recommendations.

Testing in a joint environment

What is testing in a joint environment? Why is it important? The short answer to both questions: to test as we fight. For most of the twentieth century, the U.S. Air Force, Army, Navy, and Marines fought wars together by coordinating separate air, land, and sea operations. Such separate operations preserved traditional service roles but did not always take advantage of synergies among service capabilities. Starting in 1991, with Operation Desert Storm, and continuing through today's operations in Afghanistan and Iraq, commanders from one service have been compelled by circumstances to conduct operations jointly with other services. While such joint operations have clearly proven to be more effective than separate service operations, joint operations also reveal incompatibilities of individual service systems (hardware, software, or procedures) with one another. To eliminate incompatibilities in future systems, the Secretary of Defense changed the way new military systems are justified, developed, and tested. This new requirements initiation system (Department of Defense, 2003a) uses a capabilities-based approach to identify gaps in the Services' ability to carry out joint missions. The Services must identify new systems to fill the gaps and must test those systems to determine whether they can support joint operations. Testers will need joint environments in which to conduct such tests.

In his strategic planning guidance for 2006 to 2011, the Secretary of Defense directed his staff to determine what actions would be necessary to create new joint testing capabilities and to institutionalize the evaluation of joint mission effectiveness. The resulting *Testing in Joint Environment Roadmap* (Department of Defense 2004) identifies policy, procedures, and test infrastructure changes that would allow the services to routinely conduct test and evaluation in joint environments. Parallel policy changes require frequent testing of all systems to demonstrate joint capabilities throughout development. Procedural changes adjust the traditional methods and processes testers use to define test environments, design test events, determine measurement requirements, and establish evaluation products. Infrastructure changes are needed to overcome facility and force-availability limitations. Large forces are seldom available to participate in testing because of real-world commitments. Even if forces were available, most test facilities are simply too small.

Authors of the *Testing in Joint Environment Roadmap* quickly concluded that testing in joint environments was generally not possible at any single test facility. They saw modern networks and rapidly improving simulations as the means to overcoming single-facility limitations. Networks can make several different and geographically separated test facilities appear as one. Networks also allow operator- or hardware-in-the-loop simulators (sometimes called "virtual" simulations) to substitute for live systems, and digital computer simulations (called "constructive" simulations) to substitute for live or virtual systems in a joint environment. Combinations of live, virtual, and constructive systems—linked through networks into a single distributed environment—could form LVC joint mission environments for testing. An added benefit is that system developers can test early constructive models in an LVC joint mission environment. Those developers can continue to use the same environment for testing virtual and live prototypes as development work progresses toward production. *Roadmap* authors see the LVC mission environment as a key enabler to "testing as we fight" across the acquisition life cycle.

Traditional tests conducted by the military services have focused on verifying system-level performance requirements specified in operational requirements documents. The military services have little experience testing new systems as participating elements in a joint system of systems. As a result, processes and methods for designing and executing tests of systems of systems in joint mission environments are neither well defined nor understood. Nor is there a clear understanding of how to assess system performance as it pertains to capabilities supporting joint missions. The Director of Operational Test and Evaluation (DOT&E), as the lead Secretary of Defense staff agency for the *Roadmap* and its implementation, chartered JTEM to address the methods-and-process components of implementation.

Methods and processes for testing in a joint environment

The initial set of methods and processes developed by JTEM, and evaluated during INTEGRAL FIRE, is

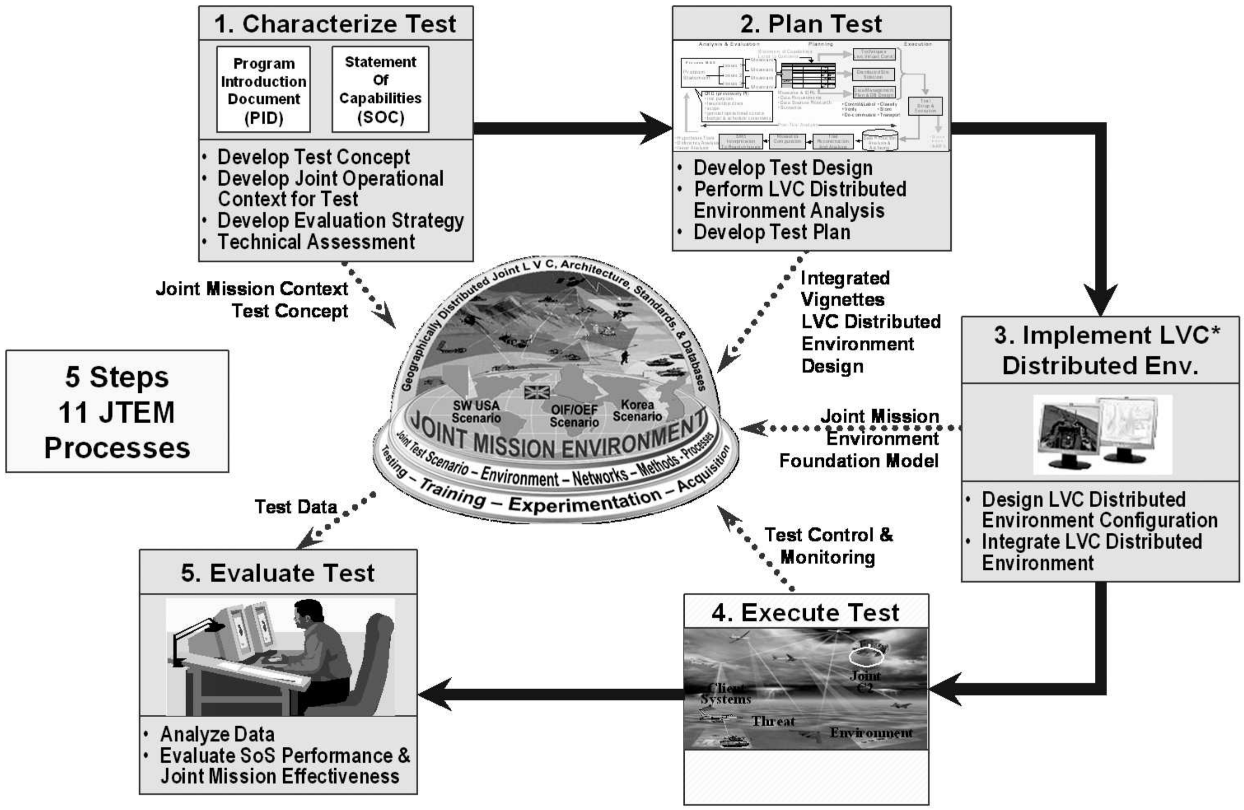

Figure 1. Capability Test Methodology version 1.0 used during INTEGRAL FIRE.

called the Capability Test Methodology (CTM) (Department of Defense, 2007a) because it goes beyond individual systems. CTM is the foundation for templates, handbooks, and other best practice guidance JTEM will ultimately deliver to test organizations and acquisition program managers regarding testing in a joint environment. *Figure 1* shows the five steps and eleven processes of which the CTM is composed. Of course, this serial depiction is a simplification of what occurs in practice. Most CTM processes are iterative in nature; many are performed in parallel, and outputs are fed back into other processes.

Nine (out of eleven) processes were the focus during INTEGRAL FIRE. These nine processes, in CTM steps 1 through 3, are important to the design and execution of systems of systems tests in a distributed LVC joint environment. JTEM did not develop step 4 processes. The other two processes, in CTM step 5, deal with evaluations of system performance and joint mission effectiveness. These were addressed during 2008. *Table 1* shows the first three CTM steps and the various output products produced by the processes. These output products were used to assemble the particular distributed live, virtual, and constructive joint mission environment for INTEGRAL FIRE.

The first two CTM steps are derived from the current processes for planning tests at a single Major Range and Test Facility Base (MRTFB) (Department

Table 1. Primary CTM steps, processes, and output products evaluated during INTEGRAL FIRE

CTM steps	CTM methods and processes	Output products
CTM 1 Characterize test	• Develop test concept • Develop joint operational context for test • Develop evaluation strategy • Technical assessment	• Program Introduction Document (PID) • Statement of Capability (SOC)
CTM 2 Plan test	• Develop test design • Perform LVC DE analysis • Develop test plan	• Test plan
CTM 3 Implement LVC distributed environment	• Design LVC DE configuration • Integrate LVC DE	• Joint Mission Environment (JME) foundation model

of Defense 2002) location. Early planning negotiations between distributed test organizations and their customers (typical program managers, for example) are conducted during CTM step 1, Characterize Test. Program characterization processes conducted by customers include development of joint operational contexts for tests, development of test concepts, and development of the evaluation strategies. Test capability characterization processes are conduced by test organizations. These processes include technical assessments that produce initial estimates of distributed test facilities needed to implement test concepts and programmatic assessments that produce initial schedule and cost estimates. Program Introduction and Statement of Capability Documents produced by CTM 1 follow formats defined by the Range Commanders' Council (Department of Defense 1997). During CTM 2, the test planning phase, test concepts are developed into more detailed test plans. Test planning processes include designing distributed tests in joint environments; refining LVC distributed test environments; and synthesizing these activities into overall test plans. In CTM version 1.0, we assume that program introductions, statements of capability, and test plans reflect the requirements of a single customer.

Joint mission environments are assembled and used to support multiple test plans (e.g., customers) during CTM steps 3, 4, and 5. Implement LVC Distributed Environment processes are concerned with technical systems engineering activities for automatic distributed LVC implementation. These processes include the design of distributed configurations, assembly of distributed components, and integration of components into a distributed LVC "test range" that meets customer requirements. In CTM step 4, the Execute Test phase, tests are conducted according to procedures and data are collected. Schedules are developed and test events are run using test planning products as inputs. This phase produces test data for customers and reusable information for future joint mission environments. Though joint mission environments are assembled to support multiple customers, tests do not have to be run concurrently. Sometimes, individual customers may separately schedule only those parts of the joint mission environment they need to meet their own objectives for testing in a joint environment. Other times, multiple customers may share a joint mission environment at the same time, for convenience or as a result of hard programmatic requirements. The latter situation was assumed during INTEGRAL FIRE. In the final step, Evaluate Test, data are processed, analyzed, and evaluated. These processes turn test data into knowledge of what happened during tests, including evaluations of joint mission effectiveness and the contributions of individual systems to joint missions.

Applying the methods and processes

We used the 2007 INTEGRAL FIRE event to develop, test, and evaluate JTEM methods and processes when those processes were used by typical test organizations under operationally representative conditions. INTEGRAL FIRE (Department of Defense 2007b) was a joint capability integration event intended to support joint test activities while working to establish persistent joint test environments. The event was jointly sponsored by Secretary of the Air Force, Warfighter Integration Directorate (SAF/XC); U.S. Joint Forces Command, Joint Systems Integration Command (JSIC); the Joint Mission Environment Test Capability (JMETC) program; and JTEM. SAF/XC conducted an assessment of the Warplan-to-Warfighter Forwarder System and its ability to support dynamic targeting. JSIC conducted a technical assessment of digital interoperability during the processing of immediate requests for Joint Close Air Support. The JMETC program coordinated network connectivity and middleware for assembling the joint test environment. JTEM test activity provided context in which to apply the CTM. INTEGRAL FIRE was coordinated through the Air Force Integrated Collaborative Environment program. Event management, led by the U.S. Air Force Simulation and Analysis Facility, was conducted collaboratively across several distributed test organizations. The test organizations that supported JTEM activity are shown in *Figure 2*.

The particular test activity planned and conducted with the CTM was intended to represent typical testing in a joint environment during early system development. As such, it was assumed the overall testing in a joint environment objective was to evaluate the contributions of two developmental weapon systems to joint mission effectiveness when those weapon systems were employed together as participating elements in an overarching system of systems. Contributions to joint mission effectiveness would then be used to determine which of the tested system design alternatives warranted further development. Constructive models of a surface-to-surface fire support platform (FSP) and an air-to-surface network-enabled weapon (NEW) were used to represent the two developmental systems. Joint Fire Support (Department of Defense 2006), including aspects of Joint Close Air Support (Department of Defense 2003b), was chosen as the joint mission. We assumed joint mission effectiveness was determined by the ability to deny employment of enemy forces (timeliness of attacks) and the ability of the system of systems to

Figure 2. Distributed test organizations used to apply JTEM processes during INTEGRAL FIRE.

attack enemy combat assets (continuity of target location accuracy across network nodes). Weapon design alternatives were defined by different data link message implementations. Different joint tactics, techniques, and procedures were used to evaluate the robustness of design alternatives to varying methods of employment—in this case different airspace coordination procedures when NEW and FSP were employed concurrently.

INTEGRAL FIRE was managed using an integrated product team and senior steering group structure. Team leaders were responsible to the overall event leader who was responsible to the senior steering group. There were six integrated product teams. The analysis team translated evaluation objectives into specific data requirements and refined joint operation contexts and conditions under which the data needed to be collected. The LVC team defined and coordinated distributed components to assemble the joint mission environment. The infrastructure team was responsible for all technical and nontechnical aspects of the networks used to connect LVC components. A security team coordinated classification guidance and assisted the infrastructure team with security accreditation. An operations team was responsible for implementing the joint operational context for test activities, including specific sequences of activities conducted by systems under test and supporting systems of systems during actual testing. Finally, an integration team provided facilitation and coordination among the other teams. All six teams applied various parts of all CTM steps. As discussed later, this has implications regarding future, persistent organizational structures for testing in a joint environment.

Planning and coordination across distributed INTEGRAL FIRE test organizations was accomplished through weekly conference calls and three face-to-face planning conferences. Each integrated product team conducted its own conference call between Monday and Thursday. Each Friday, all team leaders participated in a conference call with the integration team and event leader to coordinate actions across the integrated product team structure. The event leader also facilitated a monthly conference call composed of senior steering group members. Face-to-face conferences brought together most event participants (approximately 100 test engineers, managers, and analysts from 21 difference test organizations) to bring everyone to a common understanding of overall planning status and issues and to conduct detailed planning and integration discussions. In terms of the JTEM Capability Test Methodology, the initial planning conference focused on processes in CTM 1. The midproject and final planning conferences concentrated mostly on CTM 2 and 3, respectively. JTEM used all of these interactions among distributed

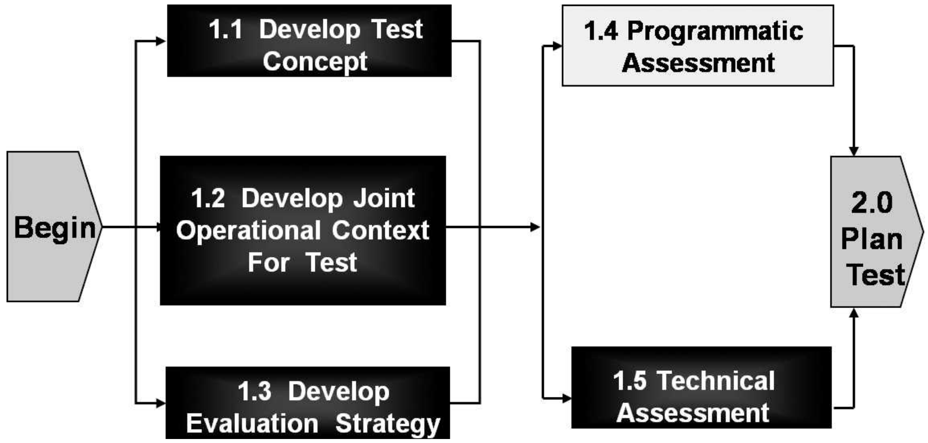

Figure 3. CTM 1 Test characterization processes used during INTEGRAL FIRE.

participants to evaluate the effectiveness and suitability of CTM version 1.0 processes, as well as to assess the applicability of the INTEGRAL FIRE organizational structure to a permanent state in which distributed tests regularly occur.

Results and discussion

CTM 1 processes, shown in *Figure 3*, were accomplished before and during the initial planning conference. JTEM personnel provided input information in the form of a test concept, joint operational context, and an evaluation strategy for focused developmental testing in a joint environment. After some iterations and negotiations between JTEM and the integrated product teams, the teams completed a technical assessment that produced an initial estimate of the distributed joint test environment.

For example, *Figure 4a* shows one of the test-concept depictions used in early program introduction information submitted to INTEGRAL FIRE teams for technical review. With assistance from JTEM engineers, the integrated product teams took this concept, along with additional information about required joint operational contexts and evaluation strategy, and produced the operational view shown in *Figure 4b*. The LVC team also produced an initial estimate of the distributed facilities needed to assemble the environment shown in *Figure 4*, and the operations team developed an initial sequence of actions to be accomplished during each test trial. It was found that current CTM 1 processes for developing joint test concepts, joint operational contexts, and joint mission evaluation strategies are too important to be confined to test characterization by distributed test organizations. Rather, these processes should be accomplished when acquisition managers are preparing the overall test and evaluation strategies or master plans. That way, testing in a joint environment can be integrated with other development and operational testing throughout acquisition phases. Another important finding was that none of the integrated product teams could produce a cost estimate for *distributed* tests. This was due, at least partially, to a lack of formal relationships among test organizations to allow for routine distributed testing. Formal agreements will likely also be needed to decide which test organizations should participate in distributed testing in a joint environment for any particular acquisition program.

CTM 2 processes used to produce a test plan for INTEGRAL FIRE are shown in *Figure 5*. These processes were executed iteratively by the analysis, LVC, and operations teams. The integration team then pulled information together from these three teams to produce an actual test plan document. The midplanning conference was the primary face-to-face meeting, augmented by several smaller meetings before and afterward. *Figure 6* shows two example outputs produced by CTM 2 processes. Here, the operational architecture in *Figure 4b* was developed into an experimental design (Gray 2007) and a detailed test vignette by the Develop Test Concept process. In addition, Perform LVC Distributed Environment Analysis processes produced a refined LVC design with detailed information about facilities and individual simulated or live entities located at each facility. In INTEGRAL FIRE, test customers (SAF/XC, JSIC, and JTEM) approved their own test plans, and participating facilities produced and approved test plans according to local procedures. We concluded that this method was too cumbersome for frequent distributed testing in a joint environment. Test organizations should consider a construct in which each acquisition program has a lead test organization designated for distributed testing. Each participating

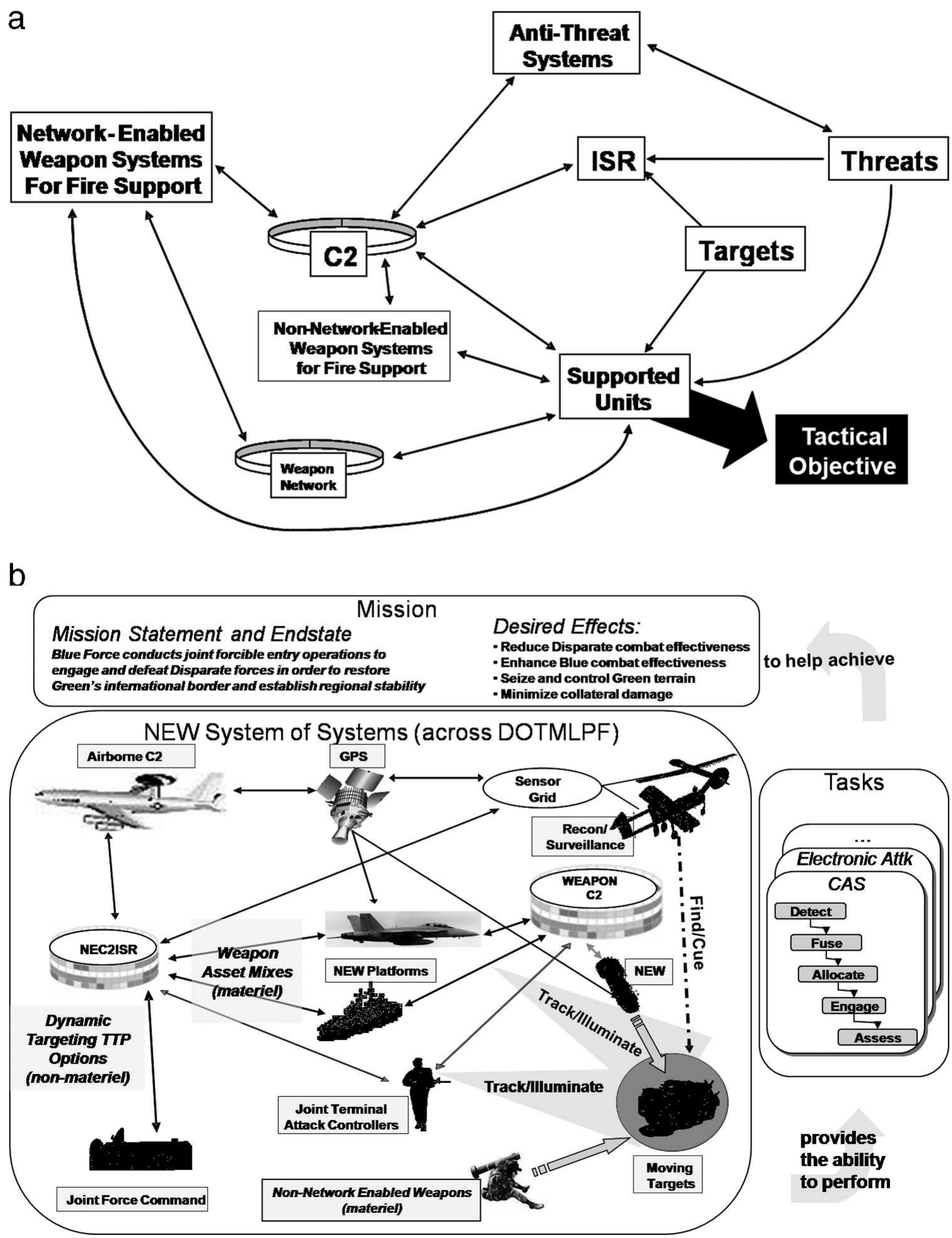

Figure 4. Inputs and outputs of technical assessment process during INTEGRAL FIRE. (a) A test-concept depiction used as input to technical assessment process. (b) Operational architecture output from technical assessment process.

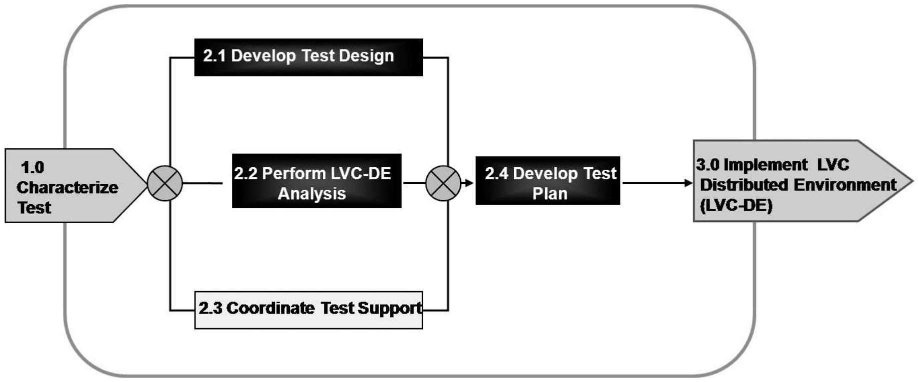

Figure 5. CTM 2 Test planning processes used during INTEGRAL FIRE.

a

Trial	ACV	Initial Airspace Assignment	First in Order	Third Party Source
1 2	Small Small	CAS CAS	NLOS NEW	JTAC Second Aircraft
3 4	Small Small	Fire Support Fire Support	NLOS NEW	Second Aircraft JTAC
5 6	Large Large	CAS CAS	NLOS NEW	Second Aircraft JTAC
7 8	Large Large	Fire Support Fire Support	NLOS NEW	JTAC Second Aircraft

b

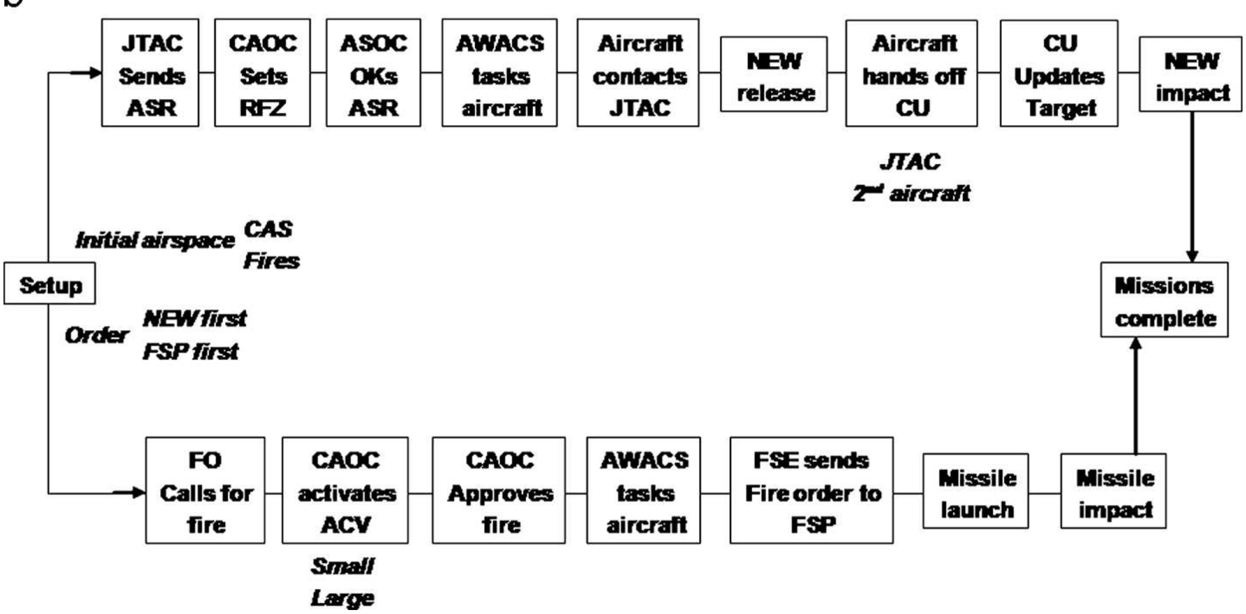

Figure 6. Outputs of develop test design process during INTEGRAL FIRE. (a) Experimental design produced by the develop test design process. (b) Vignette details produced by the develop test design process.

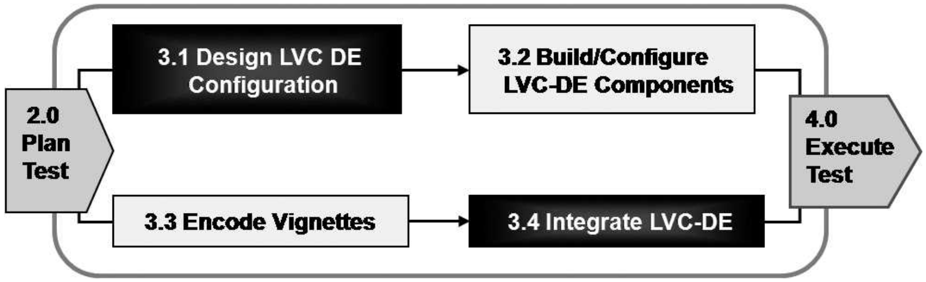

Figure 7. CTM 3 implement LVC distributed environment processes used during INTEGRAL FIRE.

test organization could produce a test plan according to local formats and procedures, with added sections to accommodate JTEM-recommended methods and processes for distributed testing in a joint environment. The overall distributed test plan could be an augmented version of the lead test organization's plan. Participating test organizations could approve their own plans, while the lead test organization commander would provide "distributed approval" by mutual agreement. Such a concept might better suit situations in which tests in a joint environment are integrated seamlessly into other developmental and operational tests. The lead test organization should be the organization responsible for most nondistributed testing for that program.

CTM 3 processes used to produce the final LVC distributed environment are shown in *Figure 7*. A final planning conference and two week-long distributed integration periods were needed to execute these processes. *Table 2* shows a simple depiction of the LVC distributed configuration produced by the Design LVC Distributed Environment Configuration process. *Figure 8* shows the LVC distributed environment produced by CTM 3 processes. This distributed environment was assembled to support all INTEGRAL FIRE customers. Customers used only those parts of the environment needed to accomplish their individual test objectives. Specifically, INTEGRAL FIRE was able to schedule JSIC testing for the first week and JTEM and WWF testing during different times the second week. This is directly analogous to configuring an open-air test range to accommodate a set of test customers, then scheduling various parts of the range separately or concurrently to conduct each customer's testing. But distributed testing, such as in INTEGRAL FIRE, requires multiple test facilities to be set up and managed as though they were a single test facility. The good news is that much of the work producing CTM 3 products was simply due to the lack of a persistent distributed test environment and standing organizational relationships to manage that environment. INTEGRAL FIRE made significant progress toward persistence. Test organizations should consider establishing formal relationships—the integrated product team structure used in INTEGRAL FIRE is a sensible place to start—so that the distributed test environment can be managed as a single facility. Evidence suggests that such things as standard data products, permanent configuration control, and a full-time verification and validation group would have substantially reduced the effort needed to assemble the INTEGRAL FIRE test environment.

Table 2. LVC distributed configuration produced by design LVC distributed environment configuration

Function	Primary configuration	Backup configuration
JTAC	WSMR	Eglin
NEW	SIMAF	Eglin
Launch aircraft	SIMAF	Eglin
NEW targets	WSMR	SIMAF
CAOC	Langley	Langley
FSP	Redstone	Redstone

Conclusion

Substantial improvements were made to our methods and processes by having experienced testers use them to plan and conduct actual test activity. Processes currently in CTM 1 for developing joint test concepts, joint operational contexts, and joint mission evaluation strategies were found to be too important to be confined to test characterization by distributed test organizations. *Figure 9* shows CTM version 1.1 in which these processes are moved to a sixth step, CTM 0, for acquisition managers to prepare overall test and evaluation strategies and master plans. A lack of persistent formal relationships among test organizations led to problems with cost estimation and increased workload in assembling a distributed joint test environment. Implementation of test planning processes during INTEGRAL FIRE was too cumbersome for frequent distributed testing in a joint environment. As a result, we recommend test organizations consider a construct where each acquisition program has a lead test organization designated for distributed testing. We also recommend test organizations consider establishing

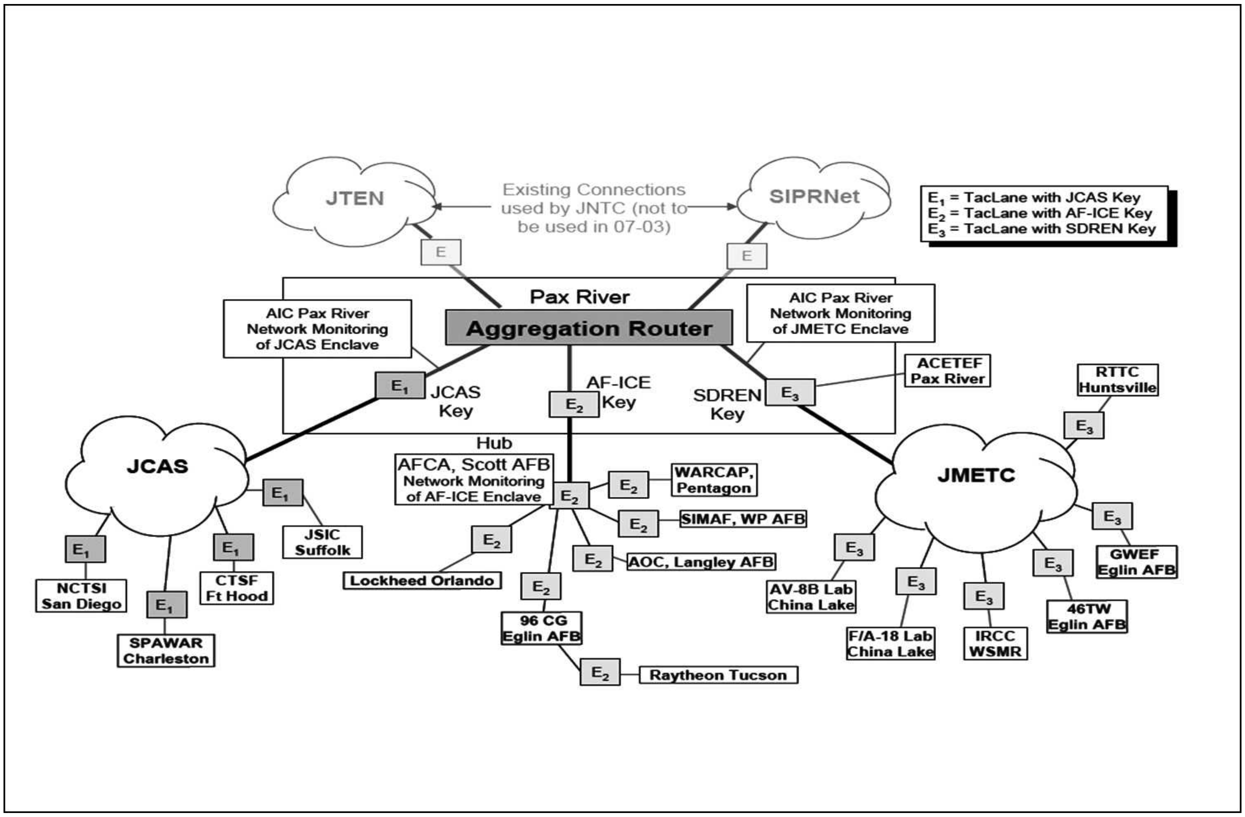

Figure 8. LVC distributed environment produced by integrate LVC-DE process.

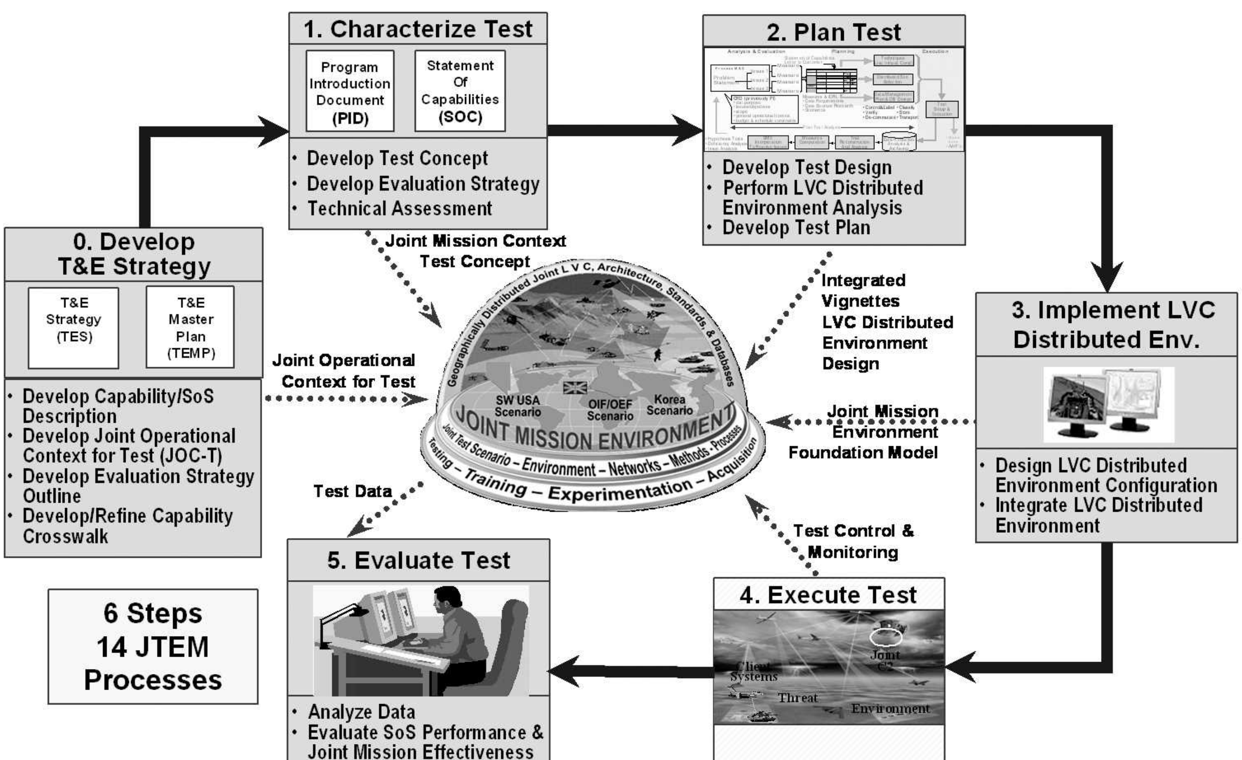

Figure 9. Capability Test Methodology version 1.1 reflecting lessons learned during INTEGRAL FIRE.

formal relationships so that the distributed test environment can be managed as a single facility. JTEM released version 2.0 of the Capability Test Methodology in early 2008 and used those updated processes to plan and conduct another set of distributed tests. The department's ultimate goal is to test and evaluate requirements as part of the overarching acquisition process in realistic joint mission environments and institutionalize testing in a joint environment. ❑

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In Search of a Common Path for Collaborative Testing

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This article presents a test and evaluation framework for developing a common path for collaborative testing. It is part concept and part application of lessons learned from field testing of radiation portal and cargo monitoring systems. As such it is not intended to be a specific how-to article. Rather, the intent is to share concepts and lay the groundwork for further development toward a common path for collaborative test and evaluation.

Key words: Test process; test framework; collaboration; CMMI; web-based test framework; data quality; Test Observation, Reporting process.

As homeland defense systems grow more complex and interdependent, the need to test and ensure their performance in a collaborative environment becomes more and more crucial. Just as these systems have grown more complex and interdependent, so too have the challenges facing professional test personnel who plan and conduct these test campaigns in a highly collaborative environment.

Because the goal for a successful test and evaluation (T&E) campaign is to ensure that only effective and suitable systems are deployed, it was determined that a collaborative T&E framework would help ensure the realization of this goal. Unfortunately, neither an existing framework nor one that could be modified to support a collaborative test environment could be found.

While searching for a collaborative T&E framework, some T&E colleagues were asking why search at all. What was wrong with current T&E methods and processes? What had changed that required a new or different approach? Certainly the T&E methods developed over the past 50 years or so were tried and true and could be used regardless of any changing trends. The questions were considered sufficiently germane that they needed to be addressed before the search for a candidate framework began.

Analysis revealed that recent trends since the events of September 11 have indeed had a major impact on the way homeland defense system test campaigns are planned and conducted. For the most part, these systems are no longer stand-alone but are all connected, or at least that is the goal. Requirements that were once fairly stable now change rapidly. While system capabilities were once defined by user requirements, now commercial off-the-shelf (COTS) capabilities determine requirements. In the past, test results affected system design; now they have limited impact on COTS designs. These trends and others listed in *Table 1* are forcing the T&E professional to rethink the old ways of testing in favor of more lean and agile methods.

Building a collaborative T&E framework

Creation of a collaborative T&E framework began with an analysis of features and benefits that an ideal T&E framework might have. The analysis revealed that an ideal framework should be universal so it could be applied by many organizations and be Web-based so it could be shared and implemented in different locations using the same processes, procedures, templates, and forms. It should be comprehensive and contain industry best practices. It should be repeatable and lean to eliminate waste (retesting) and agile to quickly adjust to changing threats. These features and

Table 1. Trends impacting T&E campaign design

Traditional T&E campaigns	Current/future trends
• Stand-alone systems	• Systems all connected (goal)
• Requirements fairly stable	• Requirements changing rapidly
• Capabilities defined by requirements	• COTS capabilities determine requirements
• Test results impact system design	• Limited impact to COTS design
• Well defined system functionality	• Complex emergent system of systems
• User community well defined	• Multiple user communities coexist
• Decisions based on test results	• Rapid deployment primary consideration
• Threat somewhat stable	• Threat continuously changing

Figure 1. Basic concept for a collaborative T&E framework (CTEF).

benefits, along with additional ones listed in *Table 2*, formed the basis for the planned T&E framework.

Armed with this list of features and benefits, a basic framework began to take shape. The framework consisting of various components took the form of a process box with input and output. The input represented a test request that could come from various sources and take on many forms, but its common feature was the requirement to evaluate a system or system-of-systems and determine its effectiveness and suitability. The framework output was defined as "quality data" or a "test report." Our analysis culminated in a concept for a collaborative T&E framework (CTEF) shown in *Figure 1*.

This basic concept along with the features and benefits of an ideal framework listed in *Table 2* provided a basis for an analysis of alternatives of several existing processes and models used in industry today. After evaluating the features and benefits of several components, three were chosen to form the basis for our CTEF: Systems Engineering (SE) process (INCOSE, 2004); Capability Maturity Model Integration (CMMI) for Development, version 1.2, (Carnegie Mellon University, 2006); and Lean Six Sigma processes and tools. The benefits that each component brings to the framework are shown in *Table 3*.

The system engineering process

The SE process component used for our framework is the one defined by the International Council on

Table 2. Features and benefits for an ideal T&E framework

Features	Benefits
• Universal	• Usable by many departments/agencies
• Web-based	• Common platform with templates
• Comprehensive	• Uses industry best practices
• Repeatable	• Not reliant on specific personnel/experts
• Lean	• Constantly eliminating waste (retest)
• Agile	• Quickly adjust to changing requirements
• Measurable	• Allow continuous improvement
• Tailorable	• Easily modified for different situations

Table 3. Selected components for the CTEF

Process/model	Benefits
Systems engineering (SE) process*	• Universally accepted framework • Repeatable processes • Tailorable • Promotes early T&E involvement • Requirements traceability key feature
Capability Maturity Model Integration (CMMI)†	• Universally accepted framework • Integrates activities across an organization • Measurable maturity levels • Dovetails nicely with the SE process • Uses industry best practices • Maturity level 4 and 5 metrics based
Lean Six Sigma process and tools	• Wide acceptance of tools & processes • Identification and removal of low value activities • Promotes both lean and agile processes • Useful for developing test CONOPS • Promotes early T&E involvement

*International Council on Systems Engineering (INCOSE) Systems Engineering Handbook v2.1, June 1, 2004; †Capability Mature Model Integration (CMMI) for Development, v1.2, Carnegie Mellon University, August, 2006.

Systems Engineering (INCOSE). The SE process provides a powerful approach to organizing and conducting development and testing of complex programs such as the radiation and portal programs. Also, this process promotes the concept of early T&E involvement in building the concept of operations (CONOPS) and analysis of user needs—a key ingredient for successful developmental and operational T&E. The SE process provides the input to the T&E framework in the form of verifiable requirements that will meet the user's needs as demonstrated in system validation. The SE process can be depicted as a V-Curve Model shown in *Figure 2*. A detailed description of the SE process can be found in the INCOSE *Systems Engineering Handbook* (INCOSE, 2004).

As comprehensive and time-proven as this traditional SE process is, it has come under attack as being myopically focused on early correctness, valuing precision over accuracy and completeness over rapid user deployment and satisfaction (Turner, 2007). So a modified SE processes was needed. By reinterpreting the SE process from an agile perspective and using timely iterative feedback and spiral development methods, the SE development process can become more responsive and leaner while still meeting user needs in a timely fashion. (The description and implementation of these methods to make the SE process more lean and agile is still a work-in-progress and beyond the scope of this article.)

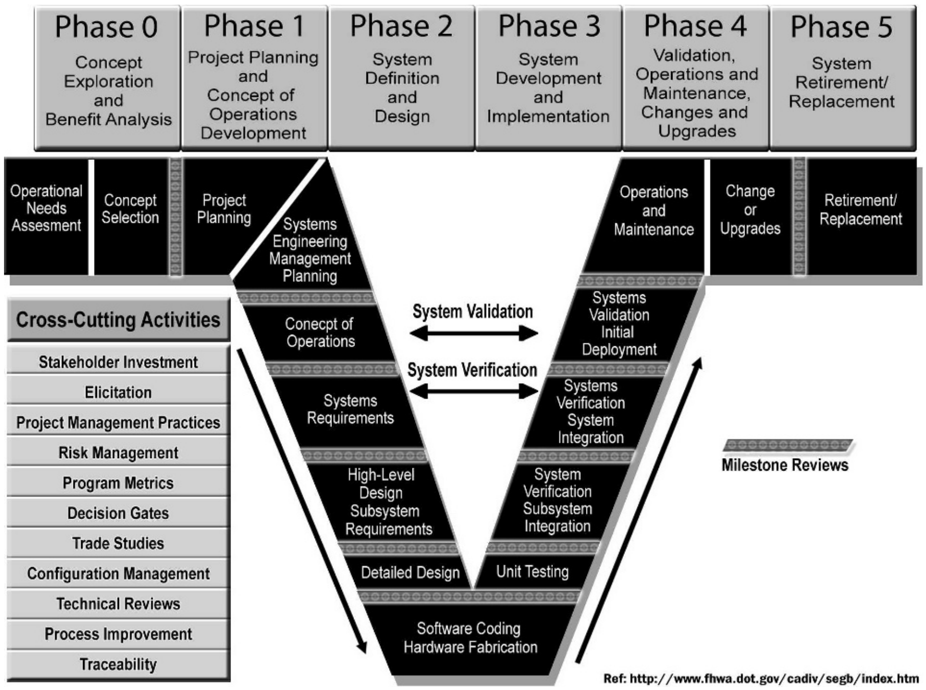

Figure 2. Systems engineering V-curve model.

Capability maturity model integration

The next major component of the T&E framework was introduced by way of industry best practices contained in the CMMI. CMMI is itself a framework for managing processes and integrating activities across an organization. By organizing the processes in this way, repeatable activities are documented and can be used by all acquisition and T&E organizations. The aspect of the CMMI process that includes T&E is part of the engineering framework as shown in *Figure 3*. Here, the technical solution is verified in Developmental Test and Evaluation (DT&E) and product integration is validated in operational test and evaluation (OT&E). A detailed description of CMMI can be found in Carnegie Mellon University, 2006.

Lean Six Sigma Process and Tools

The final component of the CTEF was to apply lean Six Sigma process and tools as shown in *Table 4*. Lean provides efficient and effective metrics and tools like Value Stream Analysis that promote quality and allow tailoring to make the framework more responsive to rapidly changing requirements.

Putting the component pieces together

The results of this building block approach resulted in the Web-based Lean/Agile CTEF shown in *Figure 4*. All three of the supporting components to T&E in *Figure 4* have strong foundations in industry with models and standards that are widely accepted. Together, these components provide all the features and benefits desired in an ideal framework. The T&E process in the center of the framework links with the other three components creating a synergistic environment that is repeatable and tailorable, and can be universally implemented on a Web-based platform, creating a virtual T&E environment for planning and analysis purposes.

T&E Process

The T&E process referenced in the center of the framework is similar to the one defined in Department of Defense acquisition documents and in the INCOSE and CMMI manuals. T&E as defined for this framework consists of both developmental and operational T&E. Short descriptions and process flow T&E for this framework are provided in the following paragraph.

Developmental test and evaluation (DT&E) for the CTEF is a process, as shown in *Figure 5*, to determine if the system was built right or if the system meets its specified requirements. Inputs to the process include the concept of operations requirements as detailed in the system specification, the integration or deployment plan, and the detailed system design. Constraints to DT&E may include items from the project or Acquisition Program Plan, Configuration Management Plan, and the Systems Engineering Management Plan. Enablers would include stakeholder involvement, the test planning working group, requirements traceability matrices, CMMI activities, and Lean Six Sigma

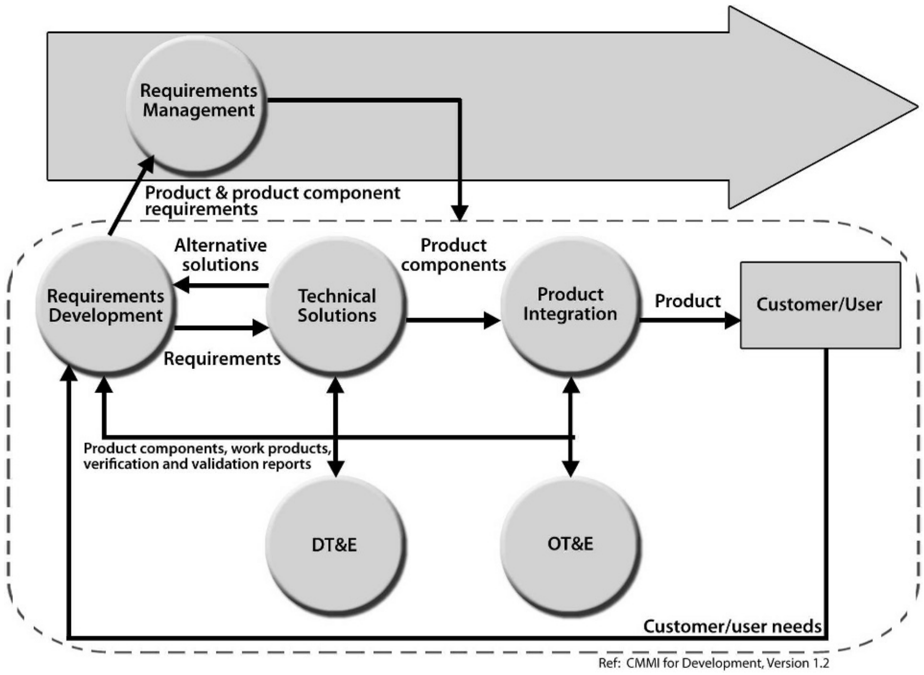

Figure 3. CMMI engineering framework with T&E.

Table 4. Some Lean/Agile Six Sigma tools for T&E

Lean Six Sigma process/tools	T&E use
• Value stream analysis	• Data quality flow determination
• Spaghetti maps	• Test procedures development
• Voice of the customer	• Test CONOPS creation

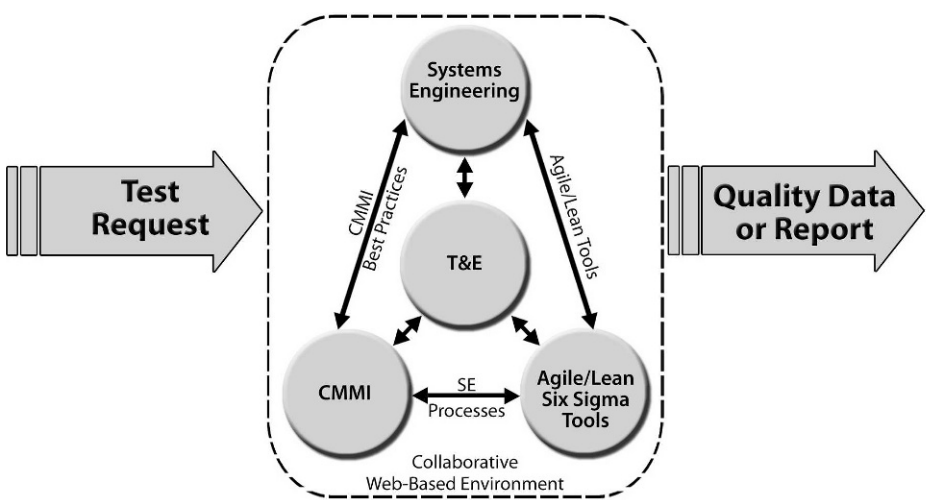

Figure 4. Lean/agile collaborative T&E framework.

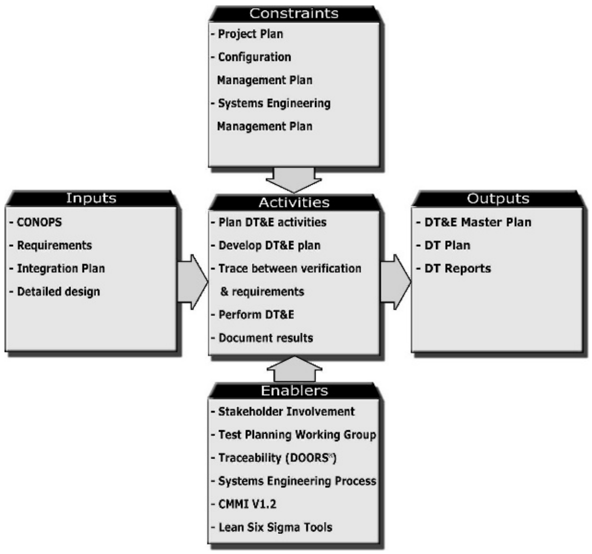

Figure 5. DT&E process flow model.

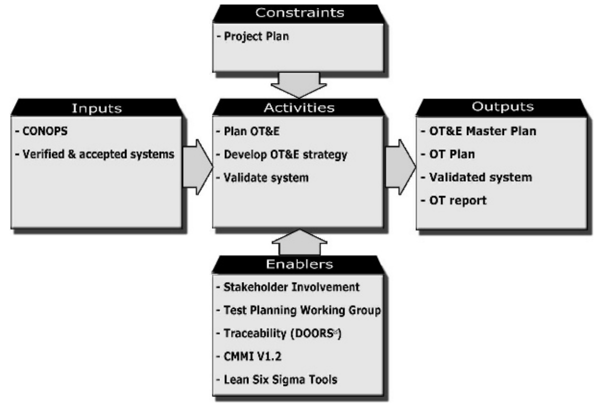

Figure 6. OT&E process flow model.

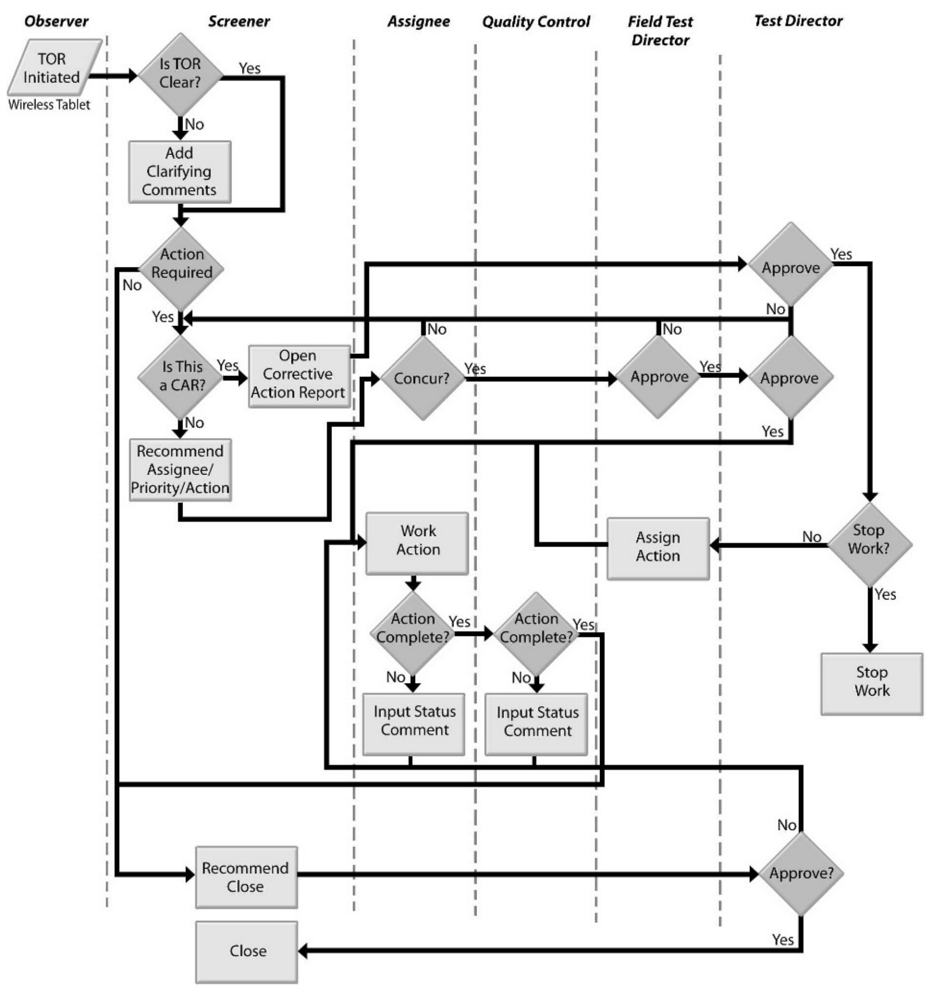

Figure 7. Lean & agile TOR process.

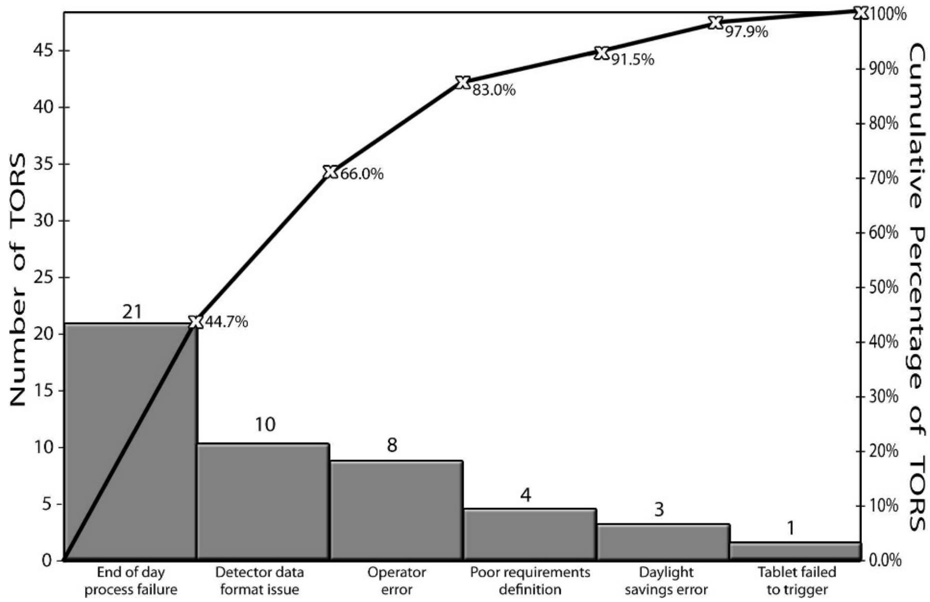

Figure 8. Types of daily errors collected.

tools. The activities in DT&E would include developing the DT plan, tracing requirements to the DT&E plan, performing DT&E, and documenting the results. The outputs of DT&E would include a test master plan or test and evaluation master plan (TEMP), campaign DT plan, and DT report.

Operational test and evaluation (OT&E) for the CTEF is a process, as shown in *Figure 6*, to determine if the system is effective and suitable for the user. Inputs to this process would include the CONOPS and the verified system from DT&E. Constraints would be limited to the project plan, which may include cost and schedule considerations. Enablers to OT&E would include stakeholder involvement, the test planning working group, CMMI validation activities, and Lean Six Sigma tools. The activities in OT&E would include developing the OT&E plan and strategy and validating the system. The outputs of OT&E would include the OT&E master plan or the OT section of the TEMP and any campaign OT&E plans. The OT report and the validated system would also be part of the output of this process.

Applying the T&E framework

With the beginnings of this framework in hand, planning for the next phase of advanced radiation portal testing began. A simple example of applying the T&E framework was the creation of a lean and agile Test Observation Reporting (TORs) process using wireless tablet computers to collect data.

In this implementation of the TOR process, improvements and lessons learned during testing were implemented in an almost near–real time fashion, allowing a more rapid improvement in data quality during the actual test while ensuring test configuration control. *Figure 7* depicts a simplified swim-lane chart of the TOR process that was developed for this test campaign in line with the CTEF.

TORs were submitted through the automated data collection system by observers, data collectors, and data quality control personnel. A TOR screener reviewed the input to determine if it required corrective action or if it was simply a test observation. The key to rapidly improving the test quality was the assignment and tracking of actions. The screener assessed the impact of any corrective actions on the testing and made recommendations to the test director. Overall, the process served to control the test configurations. To ensure that any corrective actions were properly implemented, we included verification by the Quality Control team to oversee all corrections.

The implemented TOR process provided metrics for implementing systematic fixes to the data collection process and drove down overall errors. As shown in *Figure 8*, 66 percent of all errors could be traced to end-of-day data processing and problems with incon-

Table 5. Data quality improvement

Metric title	2005 test	2007 test
No. of systems under test	10	3
No. of observations (data records)	24,000	8,605
No. of days to validate test data	35	24
Data error rate	7.0%	0.1%

sistent data formats across the systems under test. By focusing on correcting those problems, the test team significantly reduced the number of data errors.

Table 5 shows improvement in data quality from 2005 testing to those tests completed in 2007, after the CTEF was initiated. The most significant improvement appeared in the data error rate. In 2005, the error rate was 7 percent, while in 2007 the error rate dropped to only 0.1 percent. This significantly lower data error rate provided a more solid foundation for test analysis, model validation, system assessment, and subsequent acquisition decisions.

Summary

As homeland defense systems grow more complex and interdependent, the need to test and ensure their performance in a collaborative environment becomes more and more crucial. By combining the INCOSE Systems Engineering process, the CMMI framework, and Lean Six Sigma process and tools with the T&E process, a tailorable lean and agile Web-based framework was created that included all of the features and benefits an ideal framework would possess toward a common path for collaborative T&E. By implementing this framework on the Web, a virtual T&E collaborative, measurable, and repeatable environment was created that allowed sharing of information and enhanced communications among the many and varied T&E organizations.

While the framework is still a work-in-progress and more development is required, additional benefits have already started to materialize. For example, the Web-based framework provides a comprehensive training and educational platform for all test personnel supporting test campaigns for radiation and portal systems. This helps to promote a common understanding and implementation of processes, procedures, templates, and checklists, which would be difficult to achieve in the highly collaborative T&E environment.

As previously mentioned, this was not intended to be a "how-to" article. Rather the intent was to share lessons learned and lay the groundwork for further development toward a common path for collaborative T&E. It is believed that the CTEF concept provides a step in that direction. ❑

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A Systems Approach to Achieving World-Class System Integration and Test Capability

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A critical role of a test and evaluation (T&E) organization is to detect defects and remove them from systems prior to deployment to meet operational needs and achieve customer satisfaction. However, the escalating cost of systems deployment (especially in government programs) due to critical defects found in the field continues to be a major quality issue affecting customer satisfaction. This inability of programs to meet quality and program performance objectives has been linked to inadequate coordination of T&E programs. While current literature on T&E quality improvement focuses primarily on T&E technical tools, equipment, and processes, little to no attention has been paid to integrating program management with T&E. This article contributes to the state of practice by adopting a holistic approach that uses a Systemigram to analyze the current state of practice and to propose a modified model to improve the T&E program management strategy.

Key words: Managing programs; project success and strategy; test and evaluation management.

A successful test and evaluation (T&E) organization must employ effective verification and validation methods to detect defects and remove them from systems prior to deployment (Voetsch and Whitehead 2008). Although it is not possible to eliminate all defects, critical defects need to be prevented from getting to the field. Defects found in deployed systems, and the associated rework, result in the failure of test programs to meet their overall performance goals. As a result, organizations are seeking improved alternative solutions to current T&E management strategies because defects are cheaper to fix when they are found earlier rather than later in the system development life cycle.

The T&E program management strategy adopted by the organization influences the ability of a test program to minimize the cost of rework by delivering quality systems on schedule. A strategy that promotes a holistic view of both technical and management processes can result in the delivery of quality systems and help achieve customer satisfaction. However, efforts by most organizations in the past to address this issue focused primarily on verification, validation, and testing (VV&T) tools, equipment, or T&E processes, with little or no attention to integrating program management processes into the overall T&E strategy because each of these efforts seem to work in isolation.

While much has been written about how to improve the quality of test products and processes (Simmons and Wilcox 2007), the literature is limited on how to effectively integrate program management into the overall T&E strategy to enhance the output quality. To address this issue, we used a derivative of Checkland's Soft Systems Methodology (SSM), i.e., Systemigrams, to analyze the alignment of program management and T&E processes for achieving a T&E strategy within the Federal Aviation Administration (FAA).

Systemigrams identify the key elements of a formal system model with attention to parts, relationships, wholes, emergence, flows, inputs, outputs, transformations, process, and networks. The authors examined official government reports and documented artifacts relating to managing T&E, interviewed test program managers and personnel to elucidate critical requirements, and developed a Systemigram model that aligns T&E program management processes. By analyzing the current state of practice within the FAA with the Systmigram model, the authors recommended a modified model of T&E program management to improve the existing strategy.

Background

A review of relevant literature was conducted to provide the theoretical framework for analyzing the current T&E management approach and developing a proposed model.

Soft systems methodology and Systemigram application

SSM is an inquiring process that establishes the "hard/soft" distinction in systems thinking and encourages engineers to "think outside the box" about systems (Checkland 1981, 1999). In recent research to examine the extent to which SSM has been adopted in practice and to classify the literature publications, van de Water, Schinkel, and Rozier (2007) highlighted some areas where SSM has been successfully applied. SSM methodology was mostly used to gain better insight into a perceived problem situation and into problems related to the management of change with respect to organizational design and strategy formation (Ledington and Donaldson 1997; Mingers and Taylor 1992). Kreher (1994) found that SSM was most frequently applied to organizational issues relating to "participation, complexity, degree of involvement, learning, political aspects, interaction," and the use of consistent language for discussion.

The program office, the contractor, and the test organization may have a common goal to successfully deploy a system, but their respective perspectives on how to achieve that goal may vary. To understand the multiperspective stakeholder view, we must ask, "How do you encapsulate an understanding of the conceptual thinking in more than a document or the minds of many?"

While the application and variation of SSM may be an effective diagrammatic expression of conceptual thinking, it is limited in its expression of documented strategic intent (i.e., text). This is the origin of a derivative of SSM (Checkland 1999, Figure 9, 175): systemic diagrams or Systemigrams. The forces at work are exposure to systems thinking, experience in systems engineering, growing awareness of the communication complexities, and executing strategic intent.

The motivation behind the Systemigram is that a diagram can be *both* prose and diagram, and therefore has value of each within it. Most diagrams do not read well, and prose does not convey what a picture can. A Systemigram identifies the key elements of a formal system model with attention to parts, relationships, wholes, emergence, flows, inputs, outputs, transformations, process, and networks. The pragmatic merit of a Systemigram is established by virtue of its successful employment in a variety of interventions (Boardman 1994, 1995; Boardman and Wilson 2005; Boardman and Sauser 2008).

Test and evaluation program success

Relevant literature shows that lack of attention to program management issues, such as lack of inadequate planning prior to program implementation and lack of proper management, contribute to the failure of T&E programs. Also, acquisition strategies are based on poor technical assumptions, improperly phased and competing budget priorities, insufficient risk management, and unrealistic schedule expectations (Castellano 2006, 2007; FAA 2006b). Issues such as poorly defined roles, responsibilities, and authority contribute to the overall poor communications across government and industry. Additionally, the impact of political constraints on strategic planning and budgeting in government further compounds the problem of accuracy and effectiveness of program planning (FAA 2006b, Riemer 2007). The common solution is to find a better strategy for implementing testing to ensure that the T&E community can achieve future quality expectations.

The strategic objective of a T&E organization is to consistently deliver quality products to meet customer's operational needs (effectiveness and suitability) within cost and schedule constraints. Efforts to achieve program success and business objectives should start from selecting the right strategy at program initiation and aligning it with the organizational strategy (Shenhar et al. 2005). Research also shows that applying standard project management processes could increase the probability of a program achieving success (Kerzner 2000; Milosevic and Patanakul 2005; Toney and Powers 1999). The value of program management can only be achieved if it is clearly established and embedded within the enterprise structure and business management processes (Hobbs and Aubry 2007, Morris and Jamieson 2005).

Notwithstanding its familiarity and value to program success, program management continues to be one of the least understood management principles (Sherman, Cole, and Boardman 1996). Studies show that some T&E organizations have no systemic technical and program management integration (GAO 2004; FAA 2003, 2006b, 2007b). The general approach to resolving T&E performance and quality issues has been to create process improvement initiatives that end up as multiple parallel processes and quick fixes. There is hardly any evidence of any systematic approach to integrate technical and program management processes into a coordinated T&E strategy in the relevant literature. These quick fixes have not produced the sustainable strategy needed to deliver consistent quality systems and achieve customer satisfaction. To address this gap, this article uses Systemigrams to analyze and develop a model to potentially improve the capability of T&E organizations to achieve quality objectives through effective coordination.

Research methodology

The research combines the data from multiple sources with the authors' real world experiences in T&E and program management domains. A review of official government artifacts was conducted followed by interviews with various levels of organizational management. After analyzing the data, a conceptual model was developed and compared with the current T&E program management strategy.

Systems thinking concepts using the Boardman Soft Systems Methodology (BSSM) (Boardman 2006) were applied to collecting the data to elucidate critical requirements from stakeholders. Before developing a Systemigram, structured questionnaires were developed and administered to randomly selected stakeholders (test practitioners, managers, and executives). The questionnaires were analyzed by observing the patterns of current practices and by using domain knowledge of the T&E organization. Subsequently, formal and informal personal interviews with respondents were conducted to collect additional information. This information along with the document review helped to clearly define the problem.

As a human activity system, human behavior and willingness to adapt to change are critical to success in any effort that involves culture, as is the case with adopting a new strategy. Therefore, stakeholders' involvement to enhance the potential for success was emphasized in the data collection, analysis, and model design (Conner 1992). A Systemigram, part of the BSSM, is used to create a storyboard presentation to describe the model developed from initial information obtained from interviews and document review (Clegg 2007). The Systemigram presentation is a way to gain better insight into stakeholders' needs through active involvement in discussing and refining the model. The final model derived from this study is tailored to fit into the current T&E organizational culture. It can provide the necessary tools for achieving sustainable world-class system integration and test capability.

Problem situation analysis

Program managers are faced with a critical paradoxical challenge: to reduce cost and deliver quality systems that meet operational needs on time (Keegan 2005). A T&E organization is not responsible for defects found in systems while conducting verification and validation, but it is typically accountable when critical defects are found in deployed systems. The ripple effects of any program management constraint from concept and requirements definition to testing typically manifests in the T&E phase of the system development life cycle.

An internal assessment of the current T&E strategy linked the causes of critical defects found in the field to systemic inadequacies in the T&E engineering and program management process. The study found that T&E personnel are not fully involved early in the acquisition process to help ensure feasible requirements specifications and planning for effective testing. Consequently, some requirements are either not testable or not enforceable. In addition, program management constraints often force a schedule to be compressed because of overall acquisition schedule delays or funding constraints. Another major risk to T&E is the direct impact of political constraints on program management in terms of funding and schedule (FAA 2006b).

The current state assessment conducted in 2007 on T&E program management practices revealed a lack of established documented and repeatable processes needed for a disciplined approach to program management. While some improvements have been made in the area of schedule development since 2003 when the baseline assessment was conducted, there is still no established program management support infrastructure. These assessments compared the current state of practice with the Capability Maturity Model Integration (CMMI) and the Project Management Body of Knowledge (PMBOK) using the Organizational Project Management Maturity Model (OPM3). The program management support infrastructure could provide support similar to that of a program management office (FAA 2003, 2007b).

The lack of alignment between T&E and program management processes compounded by program management constraints continues to create systems quality issues after deployment. For instance, a compressed program schedule or a reduction in test funding could limit planned testing and lead to a higher probability of deploying a system with more critical defects. Apart from the exponentially higher cost of fixing critical defects found in the field compared with when they are found and fixed early during the test phase, the ripple effects cause delay in full deployment and budget overruns. The inability to deliver T&E products that meet users' operational needs and program performance metrics upsets customer satisfaction.

Hence, any new strategy designed to improve the quality of systems deployed to the field must not only address the technical issues of T&E but also deal with the program management process alignment and constraints on testing. For example, a Test Standards Board (TSB) can be established to develop and institutionalize T&E engineering processes as well as a program management supportive infrastructure to establish and coordinate institutionalized program management processes as critical enabling components of the overall T&E strategy (FAA 2003, 2006b, 2007b).

Structured text definition

This structured text was developed from reviewing relevant government artifacts and from surveys and interviews with FAA stakeholders. The primary documents used were recent reports on the current state assessment of program management practices at the FAA William J. Hughes Technical Center (WJHTC) (FAA 2003, 2007b), a white paper on a study of T&E best practices (FAA 2006), and the proposal for a Project Office implementation at the FAA WJHTC (FAA 2004). Other documents include the organizational chart for FAA WJHTC (2007b), the Air Traffic Organization (ATO) Strategy Map (FAA 2006a), and the Operations Planning (ATO-P) Strategy Map (FAA 2007a).

The structured text (BSSM) or root definition (SSM). The FAA WJHTC is developing a strategy to achieve world-class system integration and test capability that supports effective management of T&E programs to meet sponsors' expectations and achieve customer satisfaction. The strategy must address the integration of T&E technical and program management processes to facilitate the effective T&E management required to achieve program integrity, accountability, and the deployment of quality air traffic control (ATC) systems that make up the National Airspace System (NAS). The NAS is used to provide safe and efficient air transportation services to the aviation industry and the flying public. Test program sponsors' expectations are characterized by performance metrics, such as delivery of on-time and on-budget systems and meeting operational requirements (quality).

The T&E strategy must address budget overruns and late systems deployments by programs that do not meet customer satisfaction. It must minimize critical defects found in deployed systems that cause rework leading to cost and schedule variances. Critical defects are caused by inadequate testing and evaluation of systems as a consequence of the overall program management constraints.

The strategy must address the need for an integrated supportive infrastructure, which comprises a TSB and a Project Management Excellence Center (PMEC). To be credible, the supportive infrastructure must at a minimum be staffed with qualified test engineers and program (project) management experts. The TSB will develop and institutionalize technical T&E processes, while the PMEC will coordinate, develop, and institutionalize program management processes (foundational) to facilitate the technical processes. The PMEC must address training, quality management, configuration management, and project management support services that are essential for consistent and predictable program performance metrics to achieve customer satisfaction. The FAA system integration and test organization must ensure that the supportive infrastructure collaboratively provides the necessary services to accomplish the strategic objective of achieving customer satisfaction.

Systemigram model design and storyboarding

The Systemigram model in *Figure 1* translates the conceptual thinking, described in the structured text in the section titled "Structured text definition" into a conceptual model of graphics and prose. Reading from top left to bottom right is typical of Systemigrams. Strand 1 represents the primary statement with nodes, links, and relationships that describe the model objectives. It starts from the model title node labeled "System Integration and Test Organization" going through "Effective T&E Management" nodes, and ends at the "Customer Satisfaction" node as the ultimate goal. The four nodes along the mainstay are the "Program Sponsor's Expectation" for providing "Safe and Efficient Air Transportation" services to achieve "Customer Satisfaction."

Strand 2 represents the problem situation that the T&E strategy is intended to resolve with a sustainable integration and test capability. It starts by describing the nodes and links that will support the model objective starting with minimize "Critical Defects in Deployed Systems" through causes "Rework" to the "Performance Variance" node that upsets customer satisfaction. The model shows that critical defects are caused by "Inadequate Testing" of systems due to "Program Management Constraints" as issues with the current test program management strategy and potential risks to the proposed model.

Strand 3 represents the systems approach to integrate processes with a view to achieving a holistic T&E program management system. The strand starts off with "T&E Management Supportive Infrastructure" enclosing two categories of professional experts that are required by the title node to facilitate resolving the problem situation. A "Credible TSB" requires "Test Experts" to develop core T&E engineering processes. A "Credible Program Management Support

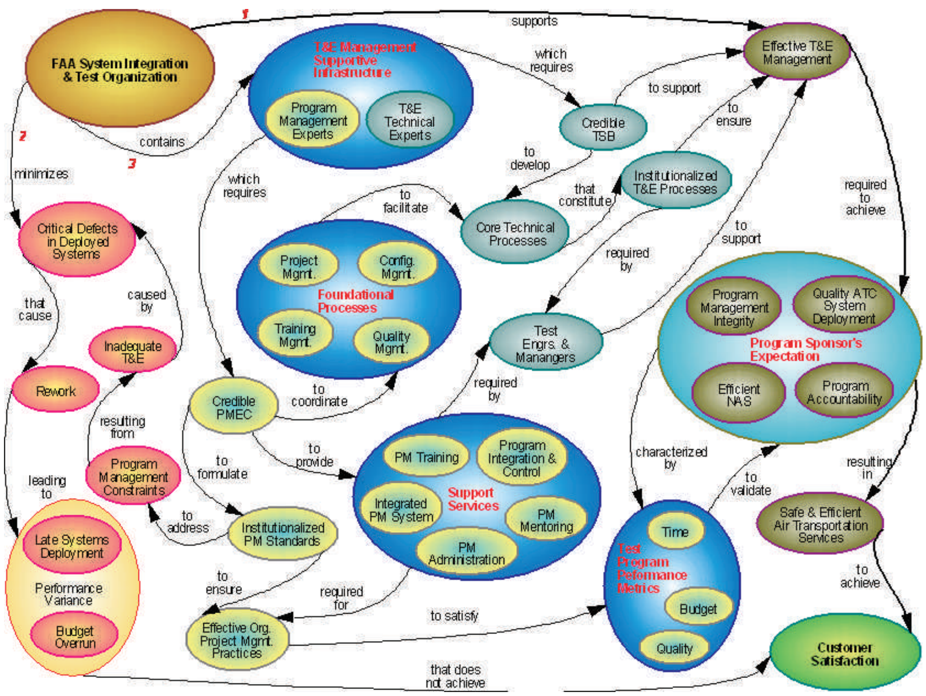

Figure 1. T&E program management model.

Center (PMEC)" staffed with qualified "Project Management Professionals (PMPs)" is also required to coordinate the program management processes that are necessary to facilitate institutionalizing an integrated T&E program management system.

Test engineers and managers in the containment node need "Institutionalized Processes" and project management support services to implement effective T&E activities. The "Credible PMEC" node coordinates the "Facilitating (Foundational) Processes" that provide "Support Services" required for "Effective Organizational Project Management." Institutionalizing project management processes will facilitate the ability to address "Program Management Constraints" and satisfy the "Test Program Performance Metrics," i.e., "On Time," "Budget," and "Quality." This strand represents the proposed "T&E Supportive Infrastructure" that integrates program management with the engineering support infrastructures as part of the overall T&E management strategy.

The storyboarding helped the stakeholders better understand the proposed model and make valued contributions in refining the Systemigram. The exchange of views helped the author gain better insight into the stakeholder perspective of the current strategy, which was used as additional input to the final model.

Proposed model implementation strategy

The problem analysis shows a lack of program management process integration and alignment to the T&E management strategy. Therefore, using a Systemigram model, we propose a T&E management strategy that incorporates the TSB and the PMEC as the core components of a T&E program management strategy. The TSB will be responsible for developing and managing the core technical T&E processes. The PMEC will coordinate program management processes with engineering processes in collaboration with the TSB. This integrated supportive infrastructure can provide managers with the tools they need to make conscious and deliberate proactive decisions on test program execution. To achieve effective coordination and credibility, executive and senior management need to demonstrate commitment by providing appropriate skilled resources and moral support for this integrated support infrastructure (Hobbs and Aubry 2007; Knutson 1999).

With the right skills available to coordinate program management processes with engineering processes, a PMEC will ensure that test programs have skilled schedulers to create and manage integrated program schedules. Each project or program may retain a scheduler, but assigning skilled schedulers from a central pool is more cost-effective because of the benefits derived from resource sharing and improved interprogram coordination (Knutson 1999). The PMEC should provide the necessary program management expert needs such as coaching and mentoring support to managers and personnel. This will enhance competency and the practical application of program management principles and techniques.

Tools

An established PMEC can help to replace the current multitude of incompatible software tools with an integrated program management system to facilitate the test program's coordination throughout the life-cycle. The system should include appropriate tools with the capability to integrate acquisition milestones with the T&E schedules. This can provide the test organization the necessary situational awareness to all programs that are coming through the acquisition process to the T&E environment. Such integration and visibility will make T&E planning and control more effective and valuable to the organization than it currently is.

Training

Providing software tools without the prerequisite training cannot achieve the desired improvement because any program management software tool is only as good as the competency of its users. Therefore, senior management in the organization needs to provide training support and incentives for PMEC personnel and T&E managers to acquire and maintain program management competency. This can be achieved through agency training, followed by internal mentoring and support by certified project management professionals. In addition, using certified Project Management Professionals (PMP) in appropriate roles requiring that level of competency and effective recognition can motivate managers and personnel to seek training and certification, which can improve their capabilities. At a minimum, the PMEC lead must maintain the continuing education requirements for certified PMPs.

Professional credibility

Both engineering and program management support infrastructures must maintain professional credibility of the experts by demonstrating value-added support to the organization. The experts should be unbiased technical and professional advisers to all stakeholders. The TSB needs to continuously research industry best practices in T&E to update current engineering processes. Similarly, the PMEC should continuously research industry best practices and update current program management and related processes.

Executive leadership

Executive and senior management need to provide the leadership and direction for program management by emphasizing the value of knowledge sharing that comes from process integration. Managers with program management training and discipline are more likely to understand the value that a program support framework brings to the organization and provide the necessary support that will facilitate the implementation of the proposed model. The implication for the organization is that effective leadership and direction by a manager with adequate understanding of program management disciple is a prerequisite for success. Establishing the PMEC at a strategic level within the organizational structure allows for executive management visibility and support. Such visibility will enhance its ability to perform the critical role of developing and implementing coordination of processes and providing program management support with adequate authority and oversight.

Continuous improvement

Implementing institutionalized best practices as proposed in the model involves compliance to processes, measurement, and continuous improvement. The success of this function requires the collaboration of the core elements of the holistic support infrastructure.

Conclusion

An examination of the current FAA T&E program management strategy was conducted to explore the best approach to help minimize critical defects in deployed systems. A systems thinking concept using BSSM was applied to the problem analysis and to develop a model with the potential to achieve quality objectives. Data were collected from government artifacts with special attention to the FAA WJHTC for the problem analysis. Using Systemigrams design and storyboard presentations, we were able to describe the conceptual model to the stakeholders and obtain additional information, which helped to gain better insight into the stakeholders' perspectives. This level of participation will facilitate the transition of the proposed model into a real-world strategy.

By analyzing the current state of practice within the FAA with our Systemigram model, we were able to recommend a modified practice to align T&E technical and program management processes to potentially optimize the T&E program management strategy. A follow-on study is planned to explore the core elements of this model and develop a detailed process integration model that can be used as a generic T&E program management framework. ❑

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Embedded Instrumentation Systems Architecture

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The objective of the Embedded Instrumentation Systems Architecture (EISA) initiative is to develop a comprehensive methodology for large-scale, nonintrusive, flexible data collection for test and evaluation needs. These needs include system-level developmental, operational, and continuous test and evaluation. The architecture can also be useful in monitoring, diagnostics, and health management, as well as protection in control applications. This article explains how EISA offers a metadata-driven methodology for heterogeneous data collection and aggregation in a synchronized and time-correlated fashion. It also describes how EISA supports real-time instrumentation and sensor management as well as virtual (synthetic) instrumentation. Finally, it addresses EISA scalability to System of Systems and/or Family of Systems embedded instrumentation applications.

Key words: Embedded instrumentation; families of systems; IEEE 1451; nonintrusive instrumentation; smart sensor technology; synthetic instrumentation; systems architecture; systems of systems; virtual sensors.

The objective of the Embedded Instrumentation Systems Architecture (EISA) initiative is to develop a comprehensive methodology for large-scale, nonintrusive, flexible data collection for U.S. Department of Defense (DoD) Test and Evaluation (T&E) needs. These needs include developmental, operational, and continuous T&E of military weapons and equipment to ensure their operational readiness both at the test ranges and during the entire life cycle of the assets.

Even though the DoD is the driving force behind this architecture, commercial, industrial, and scientific communities can also benefit from such a comprehensive nonintrusive instrumentation and data acquisition methodology in the areas of system testing, monitoring, diagnostics and health management, as well as protection in control.

This article extends the previous work presented by Visnevski (2008). It explains how EISA offers a metadata-driven methodology for heterogeneous data collection and aggregation in a synchronized and time-correlated fashion. It also describes how EISA supports real-time instrumentation and sensor management as well as virtual (synthetic) instrumentation. Finally, it addresses EISA scalability to System of Systems (SoS) and/or Family of Systems (FoS) embedded instrumentation applications.

The rest of the article is organized as follows. The next section describes the EISA from the operational and system standpoints. The third section describes the demonstration platform used in the effort to validate the first reference instantiation of the architecture. It included instrumenting and testing a high-temperature superconducting power generator. The final section offers some concluding remarks and describes future research efforts to refine the EISA and expand it beyond the scope of a single large-scale system into a SoS domain.

EISA description

The full-scale EISA description document (Visnevski 2007) contains detailed descriptions of operational, systems, and technical models of the architecture. In this article, we only highlight what we consider to be most important to the wide scientific and industrial audience aspects of the architecture.

EISA system-level description

EISA follows a conventional embedded instrumentation system model shown in *Figure 1*. In a typical embedded instrumentation system, only a minimal subset of sensors and instrument components reside onboard of the system under test. This is dictated by the limits of computational resources and available

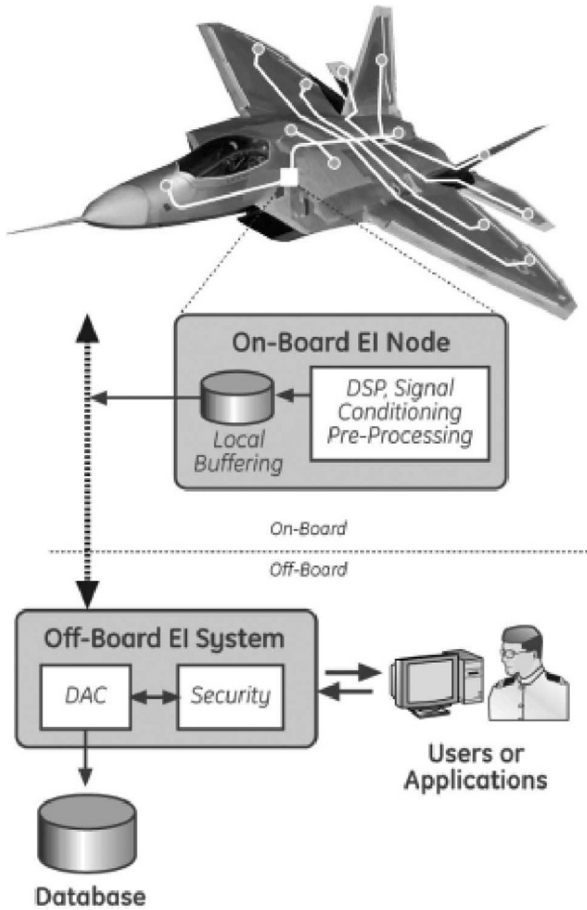

Figure 1. Typical structure of an Embedded Instrumentation System.

power onboard most mobile platforms. Instrumentation data are then preprocessed and streamed or transmitted on-demand through a telemetry network to an offboard instrumentation and data collection module. EISA follows this fundamental model. Embedded sensors and actuators of the system under test are linked to an onboard system node that is responsible for physical sensor management and initial data acquisition and post-processing activities. Then the data are transmitted over a telemetry network to the offboard data acquisition and aggregation module.

Figure 2 presents a high-level structural decomposition of the EISA-based system that is derived from the principles illustrated in *Figure 1*. Here, onboard components are represented by the Embedded Instrumentation Nodes (EI Nodes). The job of these nodes is to aggregate data from a variety of embedded legacy of smart sensors, manage these sensors, preprocess the data, and transmit the data to an offboard system over an external telemetry network. The offboard system, called the Data Acquisition and Control (DAC) unit, is responsible for aggregating sensor data from multiple EI Nodes, implementing data arbitration between various data customers and storage systems, and maintaining proper levels of security and access control to the measurement data.

Figure 3 illustrates the detailed architecture of the EI Node, and *Figure 4* shows the architecture of the DAC unit. One of the main characteristics of an EI Node in *Figure 3* is the fact that it takes advantage of the IEEE 1451 family of standards for smart sensors and transducers (Lee and Song 2003; Song and Lee 2006). The EI Node uses the IEEE 1451.X system model and extends it to support legacy instruments and sensors that are not IEEE 1451–compliant. This support is realized by a legacy transducer layer that can be custom built to any legacy sensor, transducer, or instrument. EI Nodes also take advantage of the IEEE 1451.1 concept of function blocks to implement sophisticated sensor- and system-level metadata management modules as well as modules enabling synthetic or virtual sensors and instruments.

The DAC unit shown in *Figure 4* enables sophisticated data and metadata management, system and sensor control mechanisms, distributed data storage, distributed data access, and user interface management and provides links with external applications and sensor data customers such as DoD Test and Training Enabling Architecture (TENA).

EISA brings the following advantages. It is fully metadata-driven in a sense that sensor data are accompanied by the metadata, which contains configuration and calibration parameters explaining exactly when and how the data were measured and what state the sensor was in during this time. System-level metadata describe what state the system was in during data gathering, which is critical if test results must be reproducible.

EISA enables data aggregation from a large network of heterogeneous sensors in a time synchronized and correlated fashion. EISA also supports smart sensor technology such as plug and play and sensor discovery mechanisms, directly supporting sensors compatible with the IEEE 1451.X family of standards (Lee and Song 2003; Song and Lee 2006).

Finally, EISA enables sophisticated support of virtual (synthetic) sensors. These are virtual data collection points for which a physical sensor does not exist (harsh environment or high cost prevents system implementers from using a physical sensor). In this case, physics-based modeling and simulation can be used to derive data of interest from other physical or synthetic sources in real time.

The process of Structured Analysis (Bienvenu, Shin, and Levis 2000; Levis and Wagenhals 2000; Wagenhals et al. 2000) was used to develop the EISA

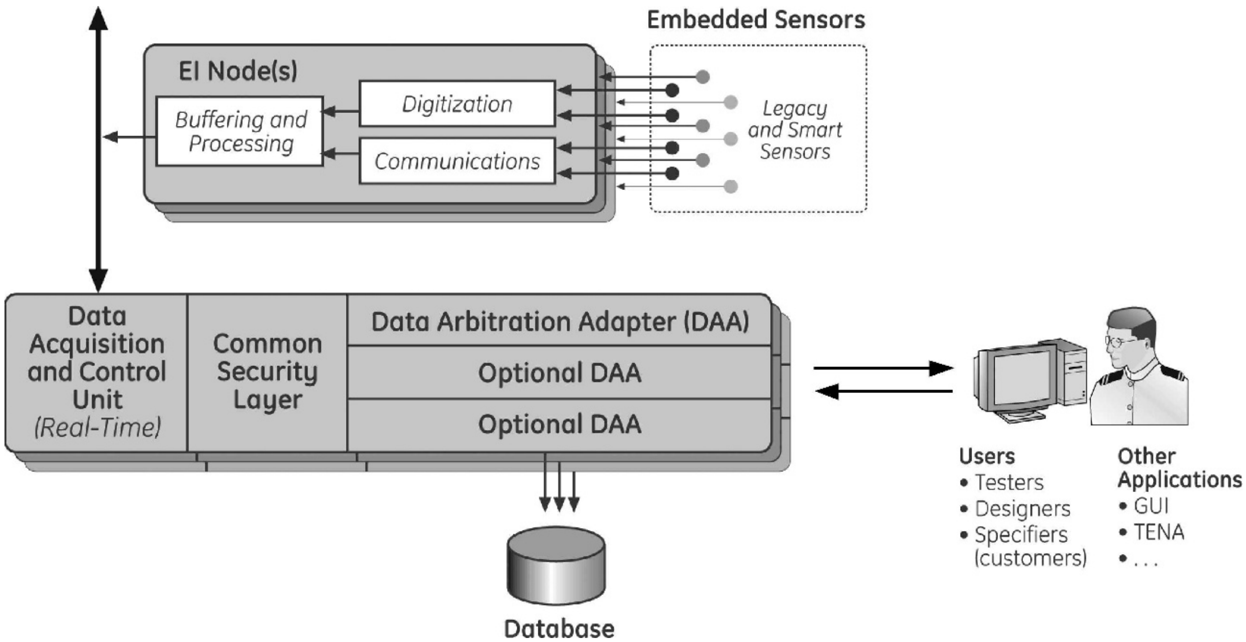

Figure 2. High-level structural decomposition of the Embedded Instrumentation Systems Architecture–based Embedded Instrumentation System.

architecture. At the high level, this process is an iterative development process that is also commonly referred to as a spiral development process. Systems architects typically use a variety of system modeling languages and tools (e.g., ANSI/IEEE Std. 1471–2000; Draft Federal Information Processing Std. Pub 83; IEEE Std. 1320.1 1998; Maier and Rechtin 2002; Object Management Group 2005) to capture the needed system models. Once systems architectures are developed, they can be documented in a series of

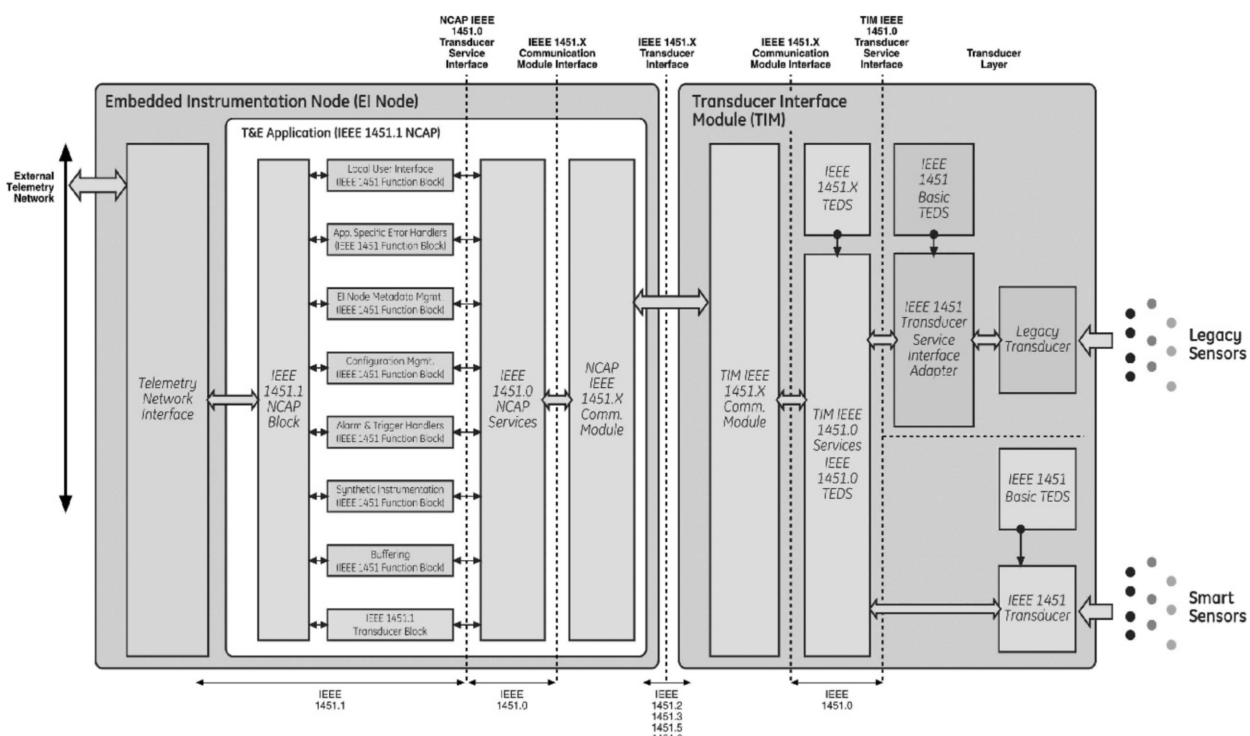

Figure 3. Embedded Instrumentation Node component of the Embedded Instrumentation Systems Architecture.

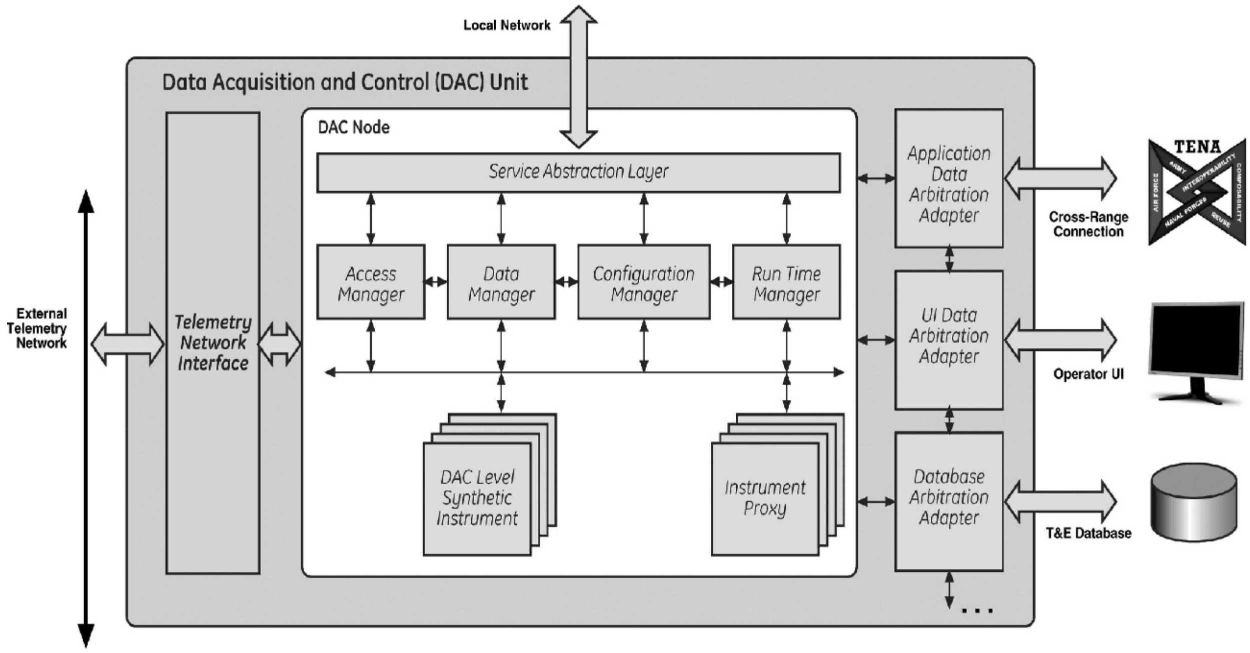

Figure 4. Data Acquisition and Control Unit of the Embedded Instrumentation Systems Architecture.

graphical or textual artifacts according to an architecture framework most suitable for the application domain of the system. We used DoD Architecture Framework version 1.0 (DoD Architecture Framework Working Group 2004, deskbook, volumes I and II; Wisnosky 2005).

EISA data model description

Data acquisition and control unit. The DAC unit class hierarchy shown in *Figure 5* describes the classes that are used to instantiate objects in the DAC unit software for particular applications. In this sense, it is a generic description of DAC unit software architecture. When the software for a DAC unit is instantiated for a particular application, this model determines the logical structure of software. Lower levels in the hierarchy inherit properties from those higher in the hierarchy, as indicated by the nature of the links.

The *EISA_Entity* is the top-level class that describes the system-level architecture (e.g., external interface types, number and perhaps types of DAC nodes, number and perhaps types of EI Nodes, their configuration, etc.). The *EISA_Service_Bridge* provides the software architectures suitable for interfacing with various network services (TENA services, Automated Test Markup Language, Sensor Markup Language [SML], Time Service, etc.). The *EISA_ExecutionManager* provides the software structures for managing the uploading of test plans, configuring and calibrating the system, executing tests, and transmitting the data to appropriate databases, while maintaining appropriate security access levels. The DAC portion of the associated class hierarchy is shown in lower levels of the central part of *Figure 5*. Finally the *EISA_Component* subclass provides the architectural components that correspond to and interface with key hardware functions of the DAC. These include, for instance, the software interfaces to the DAC node hardware and the generic EISA interfaces to external services and to the EI Nodes with which it is associated (termed "adapter classes" in current design practice).

Within the *EISA_ServiceBridge* class, several service subclasses are called out, reflecting the use of the Service Oriented Architecture concept in this design. The design pattern supporting these external services is normally termed a "bridge." The *TimeServiceBridge* class reflects the client interface software required for one or more time services; the *SecurityServiceBridge* reflects the interface software required to maintain security access to data and to the EISA system itself; the *DatabaseServiceBridge* reflects subscriptions of the EISA system to one or more databases (e.g., test plan database, runtime data repository, historical data repository, etc.). The *MarkupLanguageBridge* class refers to software used to interpret and exchange information in various markup languages, many of which are themselves the implementations of various standards (Automated Test Markup Language as part of IEEE1671, SML as part of IEEE of IEEE1641, etc.). These standards are being rationalized across services by the ARGCS (military) and IEEE1671 (commercial) working groups and others. Many of

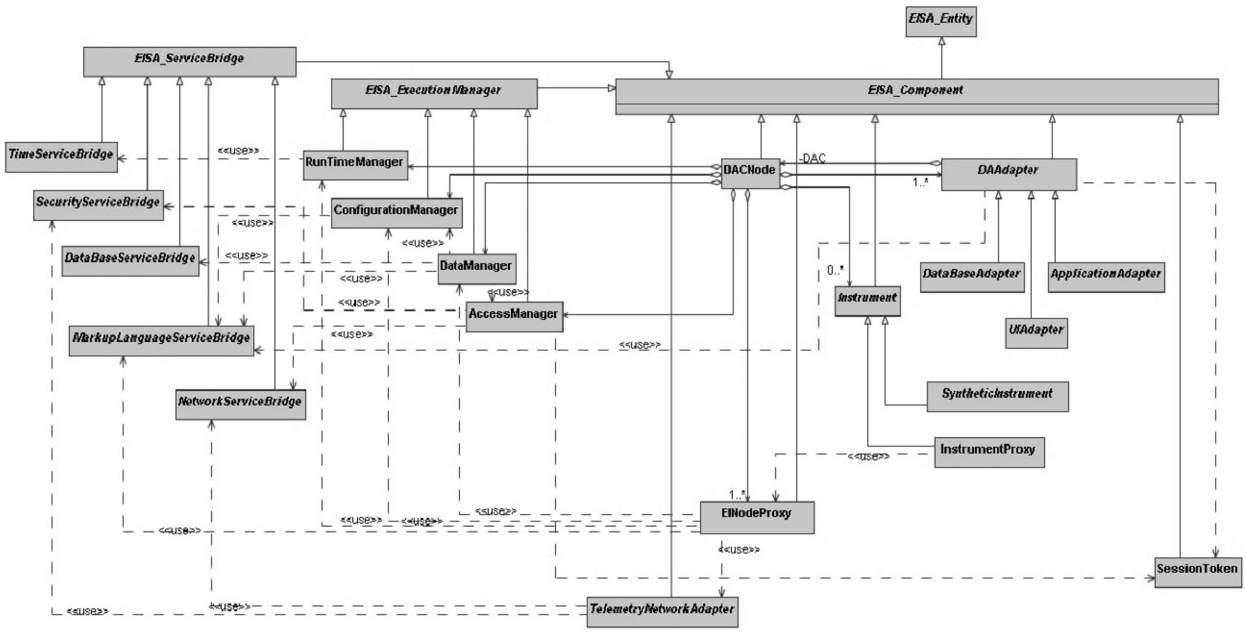

Figure 5. Unified Modeling Language (UML) model of the Data Acquisition and Control Unit of the Embedded Instrumentation Systems Architecture.

these rest on application-specific extensions of XML to provide common languages with which to transmit and understand various aspects of signals, instruments, and testing. The *NetworkServiceBridge* class relates to traditional network connectivity services and network error handling during service interruptions.

Extending the *EISA_ExecutionManager* class are several "manager" classes that are concerned with coordinating test execution. The *RuntimeManager* class is concerned with managing the process of embedded system testing itself (e.g., executing test scripts). The *ConfigurationManager* class is concerned with assuring that EISA is properly configured to execute a particular test and that equipment is ready when needed. *DataManagement* is concerned with proper routing of data, which typically will be streamed into external data files from the EINode equipment via the DAC; data routing may change occasionally during different test steps. *AccessManager* assures proper access to the DAC node and to data before, during, and after testing—note that test personnel may often require user interface access to the DAC node to confirm test readiness or to synchronize testing with nonmeasured phenomena, such as the state of mechanical equipment or readiness of test team personnel.

Extending the *EISA_Component* class are primarily the *DACNode* and *DAAdapter* classes. The *DACNode* class supports information and operations specific to a DAC Node instance (e.g., EINodes to which it is associated, local hardware/software interface methods, etc.), whereas the *DAAdapter* class supports high speed data routing to a local data repository (often accessed via backplane or a local area network) and coordination of one DAC unit with another, if required. The "Instrument" abstract class incorporates physical instruments viewed at the DAC level, as well as synthetic instruments realized at the DAC level (*DACSynthetic-Instument*) and a proxy class for instruments realized at the EINode level (*EIInstrumentProxy*), and synthetic instruments realized at the EI Node level (*EISynthet-icInstrumentProxy*), all of which may be accessed via the DAC in some cases.

The *DAAdapter* class is extended by the *Database Adapter*, *UIAdapter*, and *ApplicationAdapter* subclasses. These reflect the specific data processing needs of a particular application, including data routing during review or preview functions (*DatabaseAdapter*), different ways of viewing the test data (*UIAdapter*), and application-specific data processing (*ApplicationAdapter*).

Finally, the *TelemetryNetworkAdapter* and *SessionToken* classes provide natural extension details of the *NetworkServiceBridge* class to support secure wireless connectivity between EINodes and DAC Nodes in this project using the iNET wireless telemetry network architecture.

EI node. The "EI Node" class structure shown in *Figure 6* takes its higher levels from the *EISA_Entity* and *EISA_Component*, as previously described. It also incorporates the *Instrument* capability and *EISynthet-*

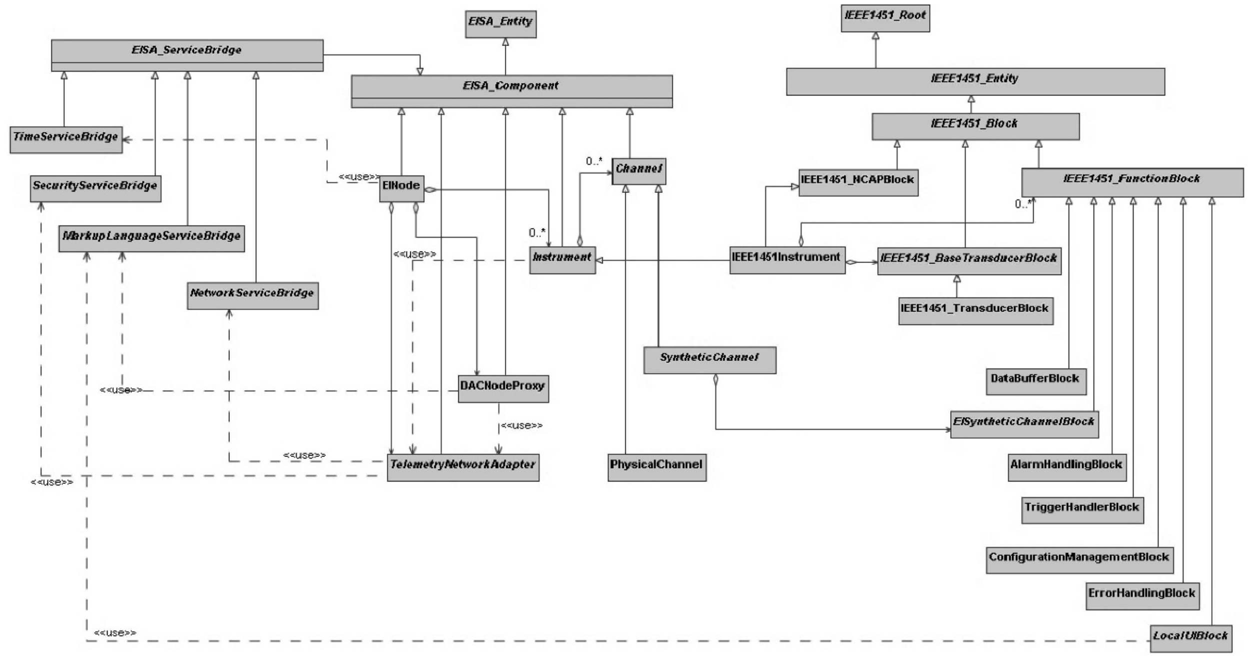

Figure 6. Unified Modeling Language (UML) model of the Embedded Instrumentation Node component of the Embedded Instrumentation Systems Architecture.

icInstrument capabilities at the *EINode* level, and 1451*Instrument* capabilities, which are standardized instrument templates supported via the IEEE1451 standard. The EI Node also specializes the *TelemetryNetworkAdapter* class and uses the *DACNodeProxy* class for secure wireless communications with its associated DAC Node. It uses a subset of the same services supported at the DAC Node via the *EISA_ServiceBridge* class, as described in the preceding section.

The low level functions of the EI Node are implemented in accordance with the IEEE 1451 Standard, as shown at the right of this class hierarchy under the *IEEE1451_Root* class. This class hierarchy is adopted here in its entirety and is identical to the class hierarchy that has been developed by the IEEE1451 Standards Committee (Lee and Song 2003). Because this hierarchy has been fully documented, only its specialization to the EISA EI Node application is discussed here. Application-specific aspects of the IEEE 1451 Standard are implemented in the *IEEE1451_NCAPBlock*, a dedicated but customizable function block within the *IEEE1451_FunctionBlock* class; the *IEEE1451_TransducerBlock* and its base class; and a set of EI Node application-specific function blocks shown at the lower right of the diagram. Precise definitions of these are provided in the IEEE 1451 Standard, but qualitatively, the Transducer Block specifies individual sensor or actuator device properties (via the TEDS data class in the metadata model), the NCAP provides the generic aspects of an interface between the EI instrument (IEEE1451.2 in this case) and a network (in this case iNET), and the application-specific blocks characterize specific behaviors of the instrument.

In the EI Node, the types of application-specific behaviors that are needed have been grouped into the *DataBufferBlock*, providing short-term data buffering; the *EISyntheticInstrument* block, providing low-level primitive instrument capabilities (e.g., multiplication or addition of signals from different sensors); the *AlarmHandlingBlock*, providing low-level alarm-handling capabilities that may be based on simultaneous conditions on several sensors; the *TriggerHandlerBlock* responsible for low-level start/stop triggering or recording of events; the *ConfigurationManagementBlock* concerned with local EI Node configuration parameters (e.g., number of associated sensors); and the *MetaDataManagement* block, in this case concerned with the description and relationships of various sensor and actuator types, the *ErrorHandlingBlock* concerned with EI Node and device-specific error handling, and the *LocalUIBlock* concerned with local viewing of particular sensor signals, e.g., for pretest checkout purposes, at the EI Node location. In the 1451 standard, this is supported generically by the XML service, but might also reflect more specialized markup languages such as SML (e.g., viewing of different signal types).

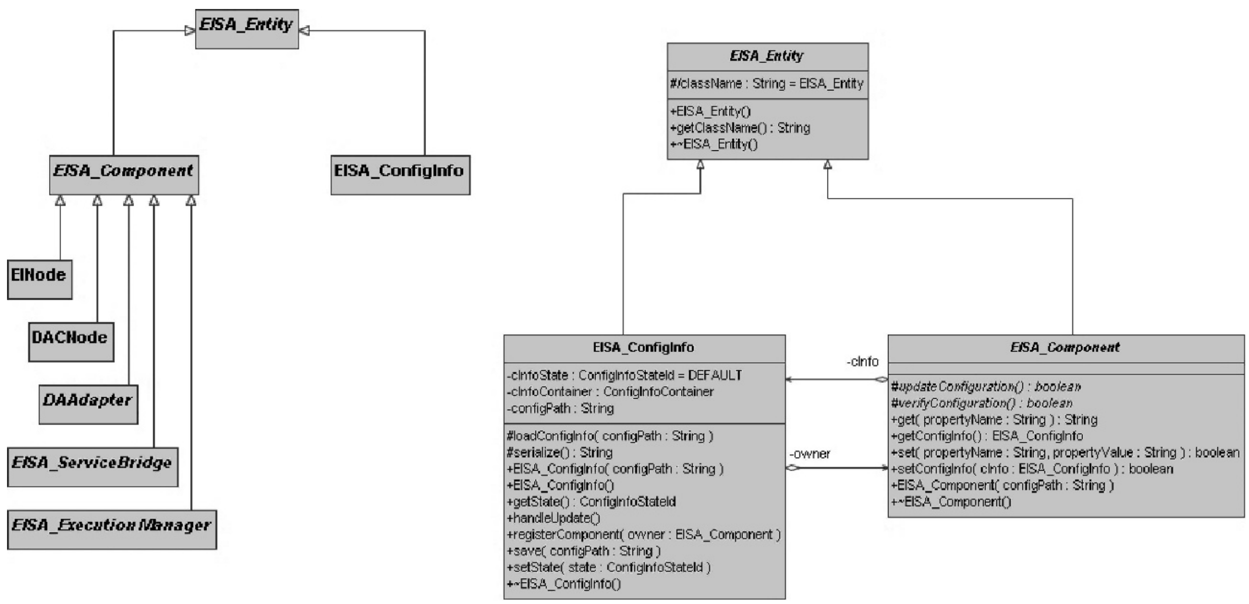

Figure 7. Embedded Instrumentation Systems Architecture use of the configuration information model.

EISA configuration information management scheme

The EISA class model is defined according to the fundamental principles of object orientation in the form of a hierarchy, with the *EISA_Entity* class being the parent class of all classes in the EISA class hierarchy. There are currently two distinct EISA entities—*EISA_Component* and *EISA_ConfigInfo*. Every element of the EISA class hierarchy belongs to one of these two types. *Figure 7* illustrates the relationships between these key EISA classes.

Figure 7 illustrates the basic EISA class hierarchy concept and demonstrates how EISA supports the concept of configuration information and metadata management. EISA exploits the duality between the concepts of configuration information and metadata in a sense that any system-level configuration information that has been successfully activated for the purpose of conducting a particular T&E activity has become the system-level metadata for the data generated during the course of this activity.

The link between an *EISA_Component* and an *EISA_ConfigInfo* is established through a circular aggregation relationship that is of fundamental importance. Each EISA component owns (aggregates an instance of) *EISA_ConfigInfo*. This ensures that each EISA component contains a unique set of configuration parameters. These parameters are loaded by the configuration manager and are validated at the time EISA component is instantiated. These parameters are accessible through "get" and "set" *EISA_Component* API methods and can be dynamically modified at runtime.

The reverse aggregation of the *EISA_Component* by an instance of *EISA_ConfigInfo* ensures that every instance of configuration information is aware of its owner and can trigger update callbacks on the owner should the content of the configuration information change. For example, a user modifies the EI Node configuration file in the configuration database. This causes an operating system callback to the configuration manager that is dispatched by the manager directly to the *EISA_ConfigInfo* class instance that was instantiated from this configuration file. The *EISA_ConfigInfo* instance then reloads itself and notifies the owner class of the change. This is supported by the "verify" and "update" API methods of the EISA component. An update method of the EI Node is called, the new configuration is verified, and is accepted or rejected based on the state of the system (see *Figure 8* for an example sequence diagram).

Note that *EISA_ConfigInfo* does not prescribe any specific configuration data fields for any specific EISA component. The idea behind it is that *EISA_ConfigInfo* is a flexible, dynamically loaded generic configuration information container that can aggregate any property-value pair style configuration information to support any EISA component in the architecture.

EISA demonstration platform

The EISA concepts described above have been applied to data acquisition in a test of a large-scale High-Temperature Superconducting (HTS) Multi-megawatt Electric Power System (MEPS). This is a high energy density device developed at GE Research for the efficient transfer of mechanical rotation energy of a turbine into

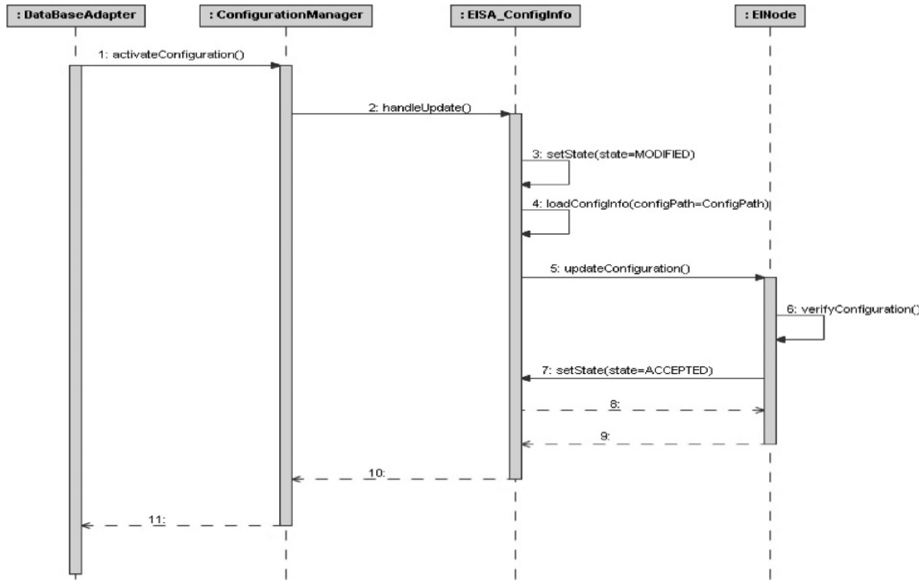

Figure 8. An example sequence of Embedded Instrumentation Systems Architecture configuration information use.

electric power at very high efficiency levels. The EISA implementation to support the test of this generator is described in *Figure 9*. The goal of this data acquisition system was to obtain high-quality, correlated, and time stamped test data for post-test analysis.

In addition to measuring physical sensor data, a number of synthetic data points and virtual instruments were implemented. One such set up is shown in *Figure 10*. It illustrates how synthetic calculation of losses enabled high-quality expected generator output power estimation that could be compared with the real output power measurements for quality assurance purposes.

EISA support of MEPS greatly simplified T&E of this system when compared to traditional data acquisition methods. All test data were time synchronized, which made it easy to analyze it after the test. Synthetic sensor values were calculated at run time and displayed alongside with the physical sensor data on a single unified and configurable user interface for monitoring and diagnostics purposes. Finally, reconfiguration of the test setup was very easy as it only involved appropriate modifications of the system level metadata that was dynamically reloaded by the EISA system, enabling flexible run-time reconfiguration. The rest of this section describes this experiment in more details.

Multi-megawatt electric power generation test platform

The MEPS was chosen as the demonstration platform for the EISA architecture because of the complexity and information-intensive instrumentation requirements for the system. MEPS is an HTS generator that can be used for a variety of applications that require high-density power generation at high rotational speeds. Mobile radar, pulsed weapons, and grid power generation are among the applications for which HTS generators are being considered for use. HTS generators are more efficient than other electric power generators because of the use of superconducting coils in the windings. The HTS generator is smaller and lighter than traditional power generators because the HTS design utilizes an air core structure that eliminates the need for large quantities of steel that other electric power generators require.

Eight instrumentation systems are used to acquire data from sensors and transmit information to legacy instruments developed by different vendors. The instruments that are supported by EISA for this demonstration include:

1. an instrument for data acquisition from flow meters, pressure gauges, thermocouples, RTDs, vacuum indicators, and pyrometers;
2. an instrument for data acquisition from vibration sensors;
3. an instrument for data acquisition from pickup coils;
4. an instrument for data acquisition from voltage sensors, current sensors, torque meter, and tachometer;
5. a web camera for video data collection.

There are approximately 175 sensors in the system. The complexity of the data acquisition system is the cause of several challenges for the MEPS testers, such as:

- Each instrument time stamps the data with a separate time stamp. If a fault occurs during

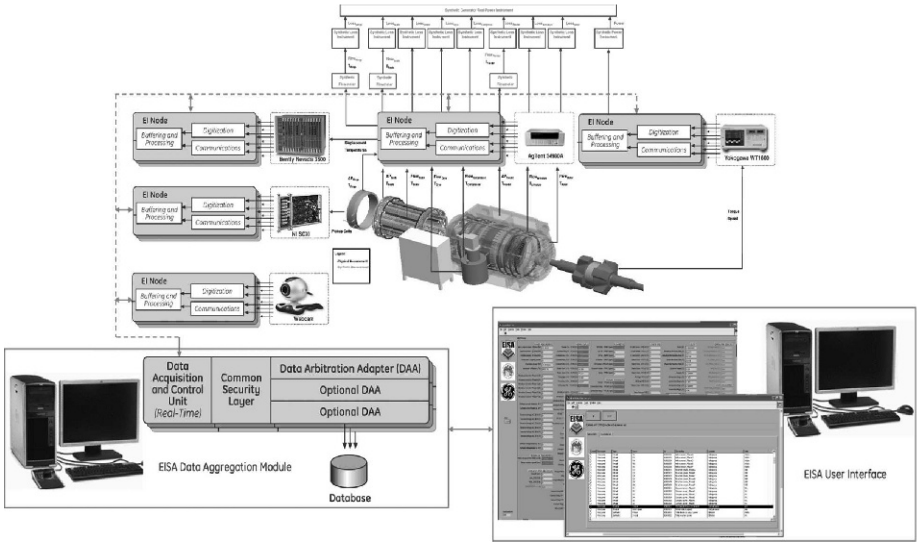

Figure 9. Embedded Instrumentation Systems Architecture Implementation of the Multi-megawatt Electric Power System Demonstration System.

testing, it is difficult to reconstruct event data at the time of the fault from different instruments because the data is not synchronized to a global time stamp.

- Legacy software often lacks flexibility to program complex equations and model-based estimates of synthetic measurements that are deduced from physical measurements.
- Each instrument requires a separate calibration and configuration process for the attached sensors.
- Visual data are dispersed across multiple GUIs operating on multiple processors.

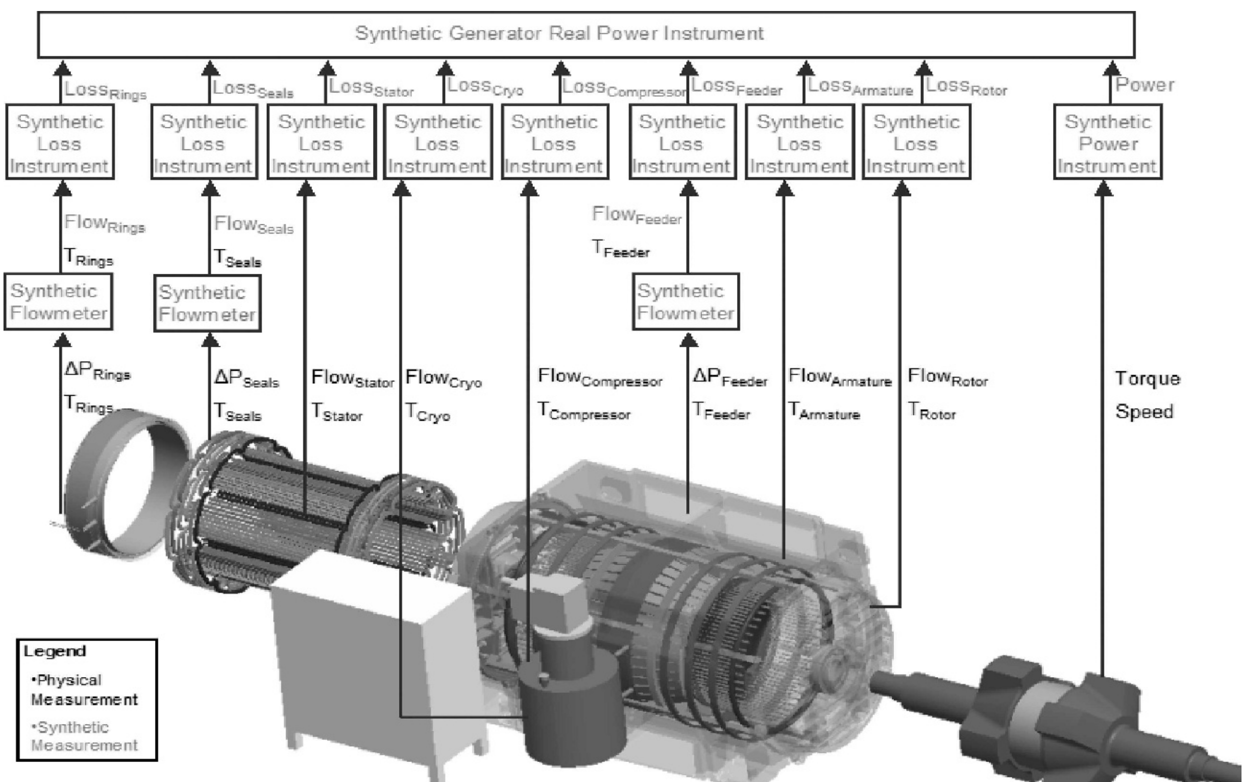

Figure 10. Logical flow of data from Multi-megawatt Electric Power System to synthetic instruments.

- Each instrument utilizes its own user authentication and data control process. Developing a comprehensive data security process is difficult.

Figure 9 shows the EISA implementation of the MEPS demonstration system. In the HTS MEPS test platform, 175 heterogeneous sensors have been embedded in a variety of the generator and test assembly components. They were wired to a set of commercial off-the-shelf data acquisition systems (Agilent, Yokogawa, Bently Nevada, National Instruments, Logitech, etc.). In this configuration, separate data acquisition systems produced data at different data rates that were not correlated, not time synchronized, were stored in different databases, and posed challenges for post-processing. The EISA-based solution involved building IEEE 1451 wrappers around the commercial data acquisition systems. This enabled continuous and integrated data and metadata aggregation for the entire test system. The test data were automatically time synchronized and stored in a single database, greatly simplifying post-test analysis.

EISA support of synthetic instrumentation in MEPS

One of the very useful properties of EISA is its inherent ability to support real-time synthetic instrumentation. EISA enables MEPS testers to integrate synthetic instrumentation to extend the capabilities of the data acquisition systems. Synthetic instrumentation of a varying degree of complexity can be implemented to compliment and extend physical measurements acquired by existing instrumentation.

Synthetic instrumentation refers to instruments that can measure quantities through numerical processing by using input from various physical sensors. Quantities measured by synthetic instruments cannot be measured directly using physical sensors because they require the combination of inputs from multiple sensors. Synthetic instruments add modularity and scalability to the architecture at a low cost because the system hardware requires minimum modification to include additional synthetic instruments in the system.

Synthetic instruments developed for MEPS are separated into two groups. The first group of synthetic instruments will use inputs from a single EI Node to measure the virtual quantity. The second group of synthetic instruments will use inputs from multiple EI Nodes that are aggregated in the database to measure the virtual quantity. These groups of synthetic instruments are shown in *Figure 10* and described in more details below.

Generator losses. Generator losses occur because of the energy expended in the generator's internal resistance and to cool various components during operation. Losses are an indicator of the generator efficiency and true output power. Thermal losses can be calculated by measuring the expended energy for the various cooling loops in the system. The generator losses include:

1. stator core losses,
2. stator bar losses
3. end winding losses,
4. connection ring losses,
5. rotor losses,
6. ferrofluid losses,
7. cryostat losses,
8. core losses in laminations,
9. pump losses,
10. feeder losses.

The data acquired to calculate the delivered power come from two EI Nodes. One node calculates the drive power via torque and speed, and the second node provides data to calculate the thermal losses in the system. All thermal losses are calculated using the general formula:

$$Energy = mCp\Delta T \tag{1}$$

Flow meters are installed in some of the cooling loops to calculate the volumetric flow rate. However, the ionized water cooling loop will not contain flow meters and will require the development of a synthetic flow meter. The delivered power at the terminals of the generator can be calculated by subtracting the sum of the system losses from the total power generated, which is equal to the product of torque and speed. *Figure 10* shows the logical flow of data from MEPS to the synthetic instruments.

Synthetic flow meter. Calculating flow rate for cooling loops is necessary to determine if the amount of coolant flowing through the system is sufficient. Flow meters are high cost instruments that cannot be placed at numerous points in the system. A synthetic flow meter is developed to measure flow using the differential pressure and temperature between the inlet and outlet of the cooling loops in the deionized water system.

Delta temperature of cooling loops. Another set of synthetic instruments is developed for thermal protection. The goal of the instruments is to measure the difference in temperature between the nominal temperature of the cooling loop and the temperature of the different components in the loop. A large difference in temperature in one section of the cooling loop can indicate a faulty cooling system that requires shutdown and maintenance.

Electrical fault detection. Early detection of electrical faults is important to protect the generator and shut down the system before damage occurs. Measuring current balance among the three-phase sets is important

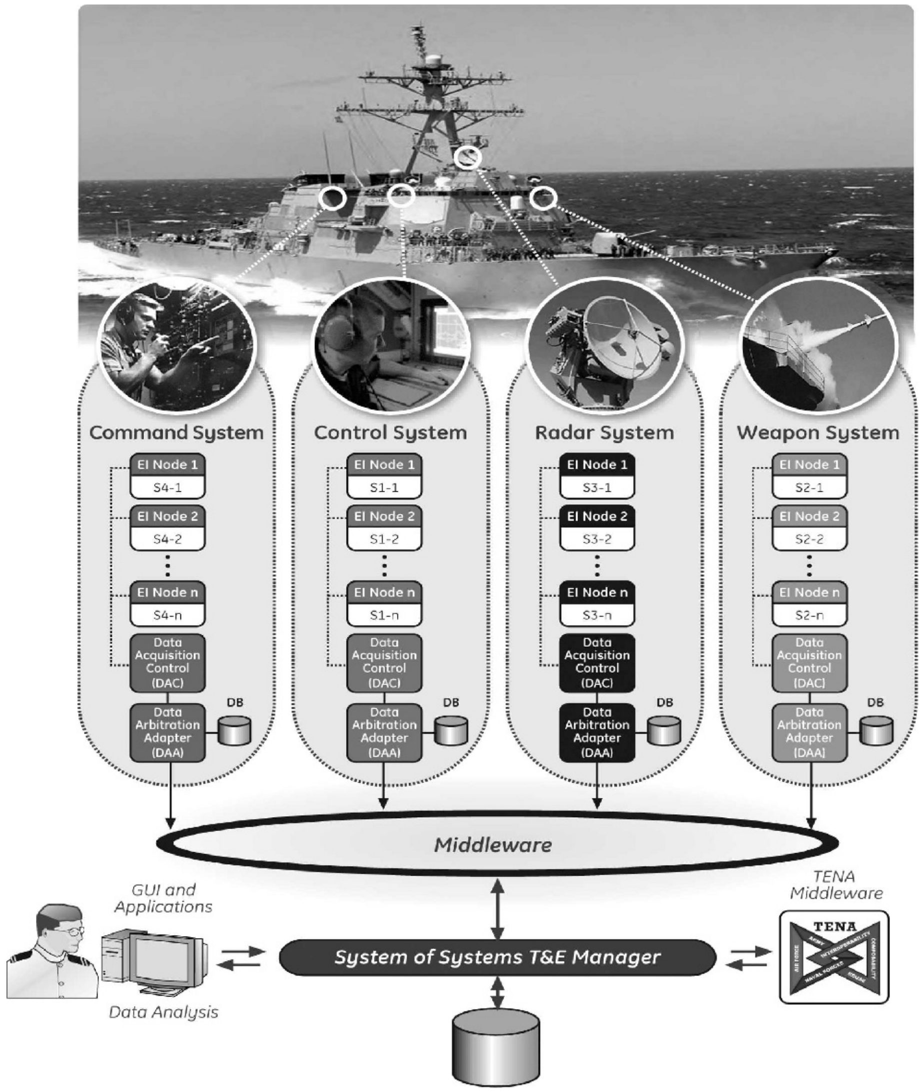

Figure 11. Embedded Instrumentation Systems Architecture System of Systems instrumentation support.

because current unbalance will cause rotor surface heating. Current unbalance can come from the individual differences of the phases in the generator, connections, and load banks. One cause of sudden current unbalance can come from the shorting of a resistor in the load bank, for example. A synthetic instrument is developed to detect current unbalance between the three phases. Another synthetic instrument is developed to detect voltage unbalance between the three phases. Voltage unbalance degrades the performance and shortens the lifetime of the generator because the voltage unbalance leads to current balance, which results in overheating of the generator as previously discussed.

The current balance of the phases A, B, and C can be verified by dividing the highest current magnitude among three phases by the lowest magnitude among the three phases followed by a division of the largest current phase angle by the lowest phase angle. If the ratio of the currents is close to one, the phase currents are balanced. The same procedure is utilized for monitoring three-phase voltage balance.

Discussions and future work

In this article, we described an architecture called an Embedded Instrumentation Systems Architecture. This architecture facilitates multirate heterogeneous data acquisition for complex large-scale system T&E. It is metadata-driven in the sense that sensor and system level metadata determine automated test system configuration dynamically at run time. It supports IEEE 1451–based smart sensor technology and provides a flexible platform for enabling real-time synthetic or virtual instrumentation. This architecture could be useful in military and commercial T&E applications as well as monitoring, diagnostics, health management, and control applications.

This article also described the application of the EISA architecture in the context of testing a single large-scale system—an HTS power generator. EISA brought substantial benefits to the generator testing by enabling seamless and cohesive integrated test data aggregation and enabling real-time synthetic measurements of test points that were not directly measurable.

The future of EISA includes work to extend the architecture beyond supporting T&E of a single large-scale system to the domain of SoS testing. This involves testing of sophisticated hierarchical test subjects such as an entire ship, airplane, cluster of unmanned vehicles, etc. GE Research is currently involved in developing this SoS architecture concept and demonstrating it on a declassified version of the command and control infrastructure of the new-generation destroyer. This concept is illustrated in *Figure 11*. Because EISA is following a centralized data aggregation path, the SoS architecture development focus is on the nodes that tie together individual DAC units associated with various data aggregation systems. This architecture component is called SoS T&E Manager (*see Figure 11*). Its goal is to preserve a coordinated data acquisition strategy across heterogeneous systems in the SoS testing framework and enable flexible control of testing process automation. ❑

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Test and Evaluation Strategies for Network-Enabled Systems

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A hierarchical series of strategies is described as an approach for testing and evaluating network enabled systems and systems of systems. The approach builds upon traditional platform performance and requirements-based testing and amplifies it to encompass the additional complexities of interacting systems with their potential for emergent behavior. It is in these interactions that the preponderance of "unknown unknowns" resides and the number of interactions grows geometrically with the size. Future tests will never be able to test a full factorial test matrix. Test and evaluation professionals must develop a systematic approach for building up results from single network nodes to complete joint systems. The hierarchical test strategies, combined with distributed testing and high fidelity live-virtual-constructive environments, are proposed as the most expedient means for satisfying network centric test requirements within time and budget constraints while mitigating technical and programmatic risk.

Key words: Hierarchical test strategies; joint network testing; global information grid; network-enabled systems; Platform as a Network Node (PANN); capability based testing; system-of-systems testing.

Test and evaluation (T&E) has traditionally involved independent platform testing of single entities. Testing is done in a serial fashion: A test would be performed, data gathered, and then the system would move to the next test center. This process is time consuming, inefficient, and insufficient for network-enabled systems. Evaluation would typically be done in a serial fashion with evaluators left to analytically synthesize how well the complete system works by fusing results from multiple test sites under multiple test conditions. For future network-enabled systems like the Future Combat Systems (FCS), however, the integration of systems-within-systems, interoperability, and networking are prime concerns, and testing requirements must be reconsidered.[1] The T&E of network-enabled systems will take new strategies like Platform as a Network Node (PANN), capability-based testing, systems-of-systems testing, and joint network testing.

Introduction

So what defines a network-enabled system? Whether it's a radiac meter sending a nuclear, biological, or chemical report, an FCS command and control vehicle with a battle-staff operating on the move, every system that has a requirement to join the Global Information Grid (GIG) or that has the net-ready key performance parameter as a requirement is a network-enabled system. This means most of the systems being built today are network enabled.

The Defense Information Systems Agency (DISA) is building the GIG as well as developing the Network Enabled Command Capability system and the Network Centric Enterprise Services. In addition, the Test Resource Management Center and the Joint Forces Command (the Joint community) are focusing on network-testing resources. These programs set the stage for understanding why standard methods are required for testing and evaluating network-enabled systems.

To understand how to incorporate these new strategies, we must have a common definition of the "Network." The U.S. Army Training and Doctrine Command and the FCS program have developed the Army definition of a network:

> *"an interconnected, end-to-end set of information capabilities and associated processes that displays,*

disseminates, stores, and manages information on demand to Warfighters, policy makers, and support personnel.”[2]

The cornerstone of Department of Defense (DoD) transformation is the ability of future forces to effectively conduct network centric operations in combat and in operations other than war. The Army program driving the need for network-enabled system testing is FCS and the complementary systems supporting it (e.g., the Joint Tactical Radio System, and Warfighter Information Network-Tactical [WIN-T]). For FCS to meet its requirement to test the FCS network, as stated in the National Defense Authorization Act 2008, SEC. 211, there must be an evaluation of the overall operational effectiveness of the FCS network including:

“(a) an evaluation of the FCS network’s capability to transmit the volume and classes of data required by Future Combat Systems approved requirements; and (b) an evaluation of the FCS network performance in a degraded condition due to enemy network attack, sophisticated enemy electronic warfare, adverse weather conditions, and terrain variability.”[3]

However, the network resides on and will operate on the FCS platforms; manned, unmanned, ground, and aerial. The FCS network therefore must be tested while on these FCS network-enabled systems. In addition, these network-enabled systems are not effective unless the users in the network-enabled systems can access the network and execute their assigned tasks while transmitting and receiving the right information to the right person at the right time in the right format, whether they are static or mobile.

To enable this, testers and evaluators need to incorporate the following strategies: PANN, capability based testing, systems of systems testing, and joint network testing.

PANN

PANN testing is a holistic, network-centric view of testing that enables an understanding of the effects of network-enabling components on the host platform, as well as the effects of the host platform on the network-enabling components as viewed in *Figure 1*. It enables an evaluator to characterize the network node enshrouded in a platform and understand how it will operate as a node of a mobile ad-hoc network. View the platform in PANN testing as a soldier, truck, tank, unmanned ground vehicle, unmanned aerial vehicle, loitering munition, or sensor that may be comprised of

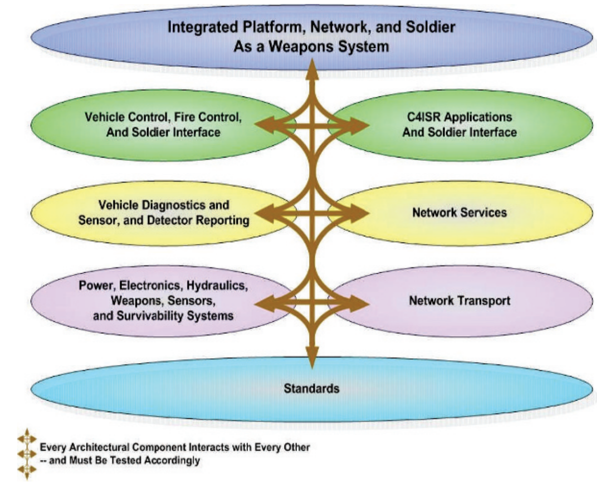

Figure 1. Platform as a network node.

one or multiple communications components or systems that have the ability to send and/or receive data.

PANN will need to incorporate new metrics like WIN-T’s communications success rate and information dissemination success rate. It will require a standard for the conduct of data dissemination with a live-virtual-constructive environment; a common synthetic environment that can be used to envelope the prototype in a network located on a virtual test center terrain. PANN will need a standard suite of models and simulations that place the vehicle in an operationally relevant environment including signatures, weather, atmosphere, sensor effects, human effects, digital terrain including natural and manmade terrain representations, full electromagnetic spectrum, soil conditions, virtual battlespace, a communications effects server to emulate not simulate multiple network nodes and traffic, Joint Program Executive Office propagation models, disturbance environments, and a composable next-generation computer-generated force toolset like OneSAF. Services should leverage what DoD has already done. For example, Army testers should not rebuild weapons models; they should use the Army Research, Development, and Engineering Command models. The Army’s test centers have almost every terrain a system will encounter. The Army Test and Evaluation Command should focus on the virtual representation of these environments, modeling the terrain to the level of detail that is needed for each variable: weather, atmosphere, obstructions, etc. To develop this correctly, each variable must be built as a service or capability to allow turning the variable on and off as the test conditions dictate. To remain in line with the Joint community, the infrastructure that ties it all together, the middleware, must be test and

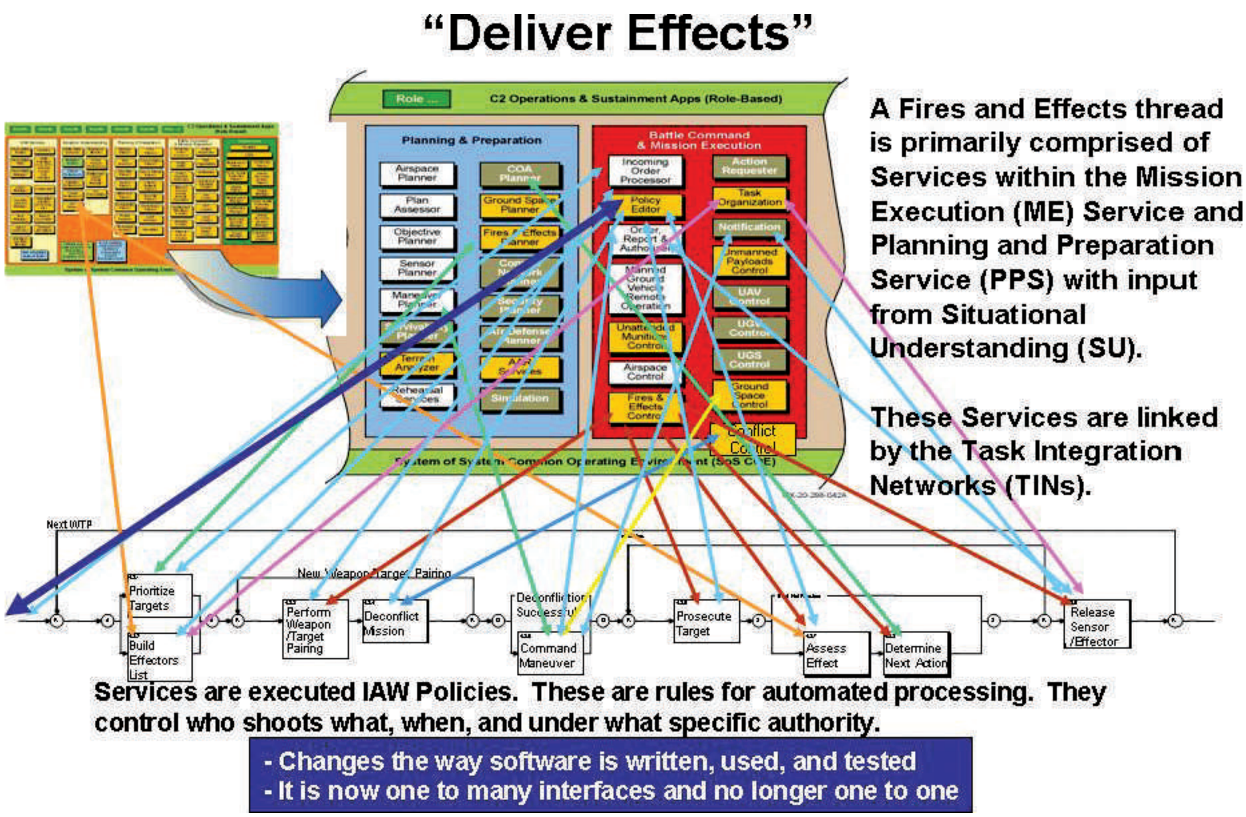

Figure 2. Capabilities based testing.

training enabling architecture[4] or at a minimum provide a gateway for high level architecture and distributed interactive simulation protocols. Modeling and simulation must also be portable to a high performance computing (HPC) system, ensuring scalability for T&E. Testers and evaluators must work together to ensure that these models and simulations have gone through the proper verification, validation, and accreditation steps to enable modeling and simulation to be used for evaluation while being executed in developmental testing.[5]

Capabilities Based Testing

Capabilities based testing incorporates the following DoD policy: "Testing and evaluation should begin early, be more operationally realistic, and continue through the entire system life-cycle."[6] Every system—manned, unmanned, aerial, soldier, or sensor—plays a specific role in the overall operation of a military unit and has designated missions. Now that these systems are becoming network-enabled, T&E must include the typical platform and systems tests plus the understanding of how that platform or system will be used and by whom. To evaluate a network-enabled system, we must have an understanding of the tasks that must be performed; the user roles, people, interfaces, and knowledge required to operate the system; an understanding of the application and service layers; and a report that all operate as prescribed and safely. To perform this type of testing, it is imperative to develop a combination of live, virtual, and constructive testing capabilities that enable mission-based tests.

Understanding the tasks and user–operators of a platform enables identification of software functionality and interfaces; addresses conflict of resources in overloaded situations between the platform and its network-enabled components; and can enable measuring the cognitive load of the user. Testers and evaluators must think in terms of vignettes: create the quantity and synchronization of threads that lead to proper network loading; create the unit of soldiers performing individual or collective tasks; and enable the measurement of human cognition and interplay in the network operation. Incorporating vignettes in developmental testing adds robustness to the vignettes planned for operational tests. This effort helps testers and evaluators understand the mission thread and capabilities-based testing. The FCS mission of "deliver effects" provides an excellent example of capabilities-based testing (see *Figure 2*).

Tester and evaluators must understand that network-enabled systems use the network application and

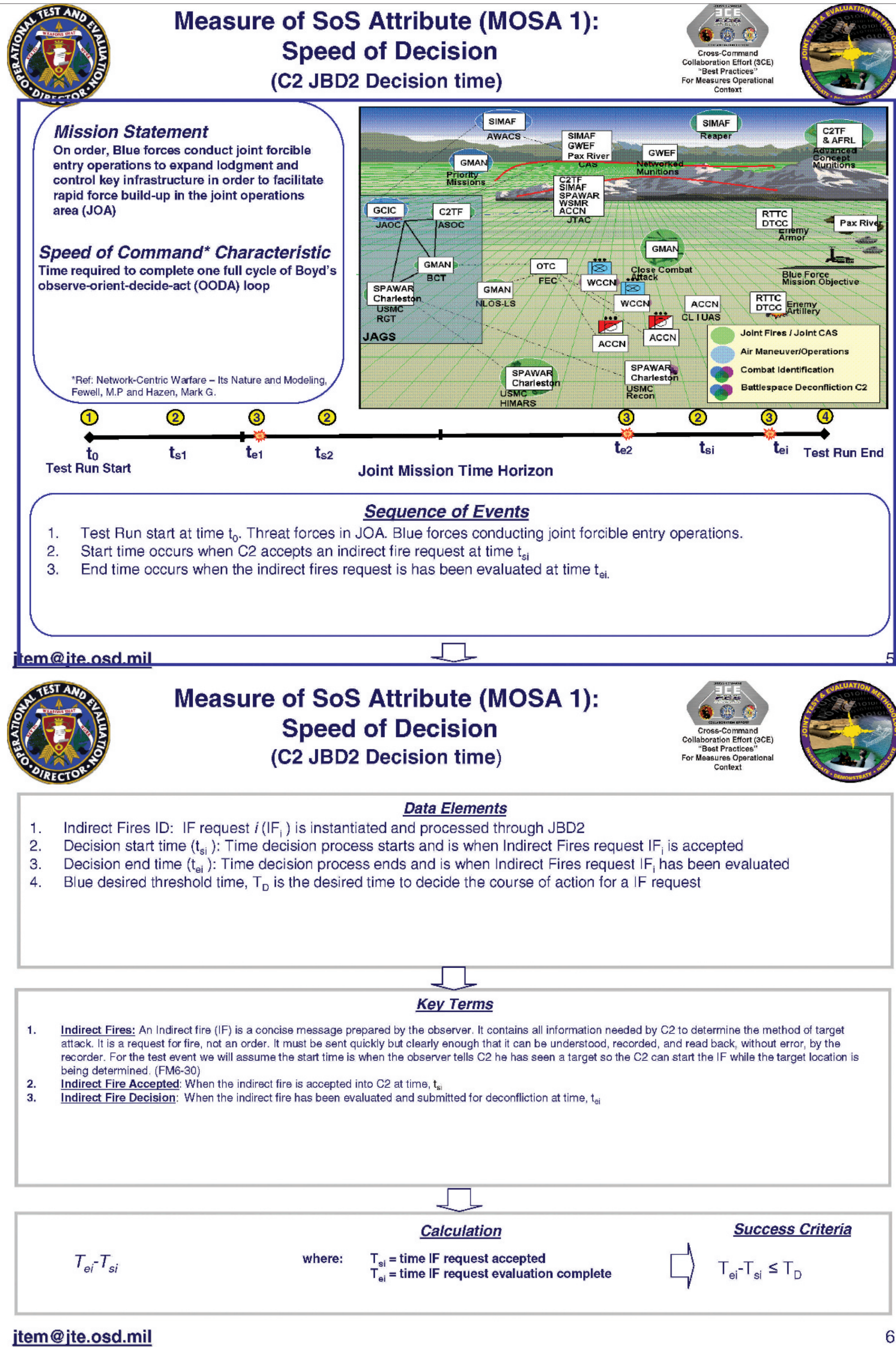

Figure 3. Common measures framework.[7]

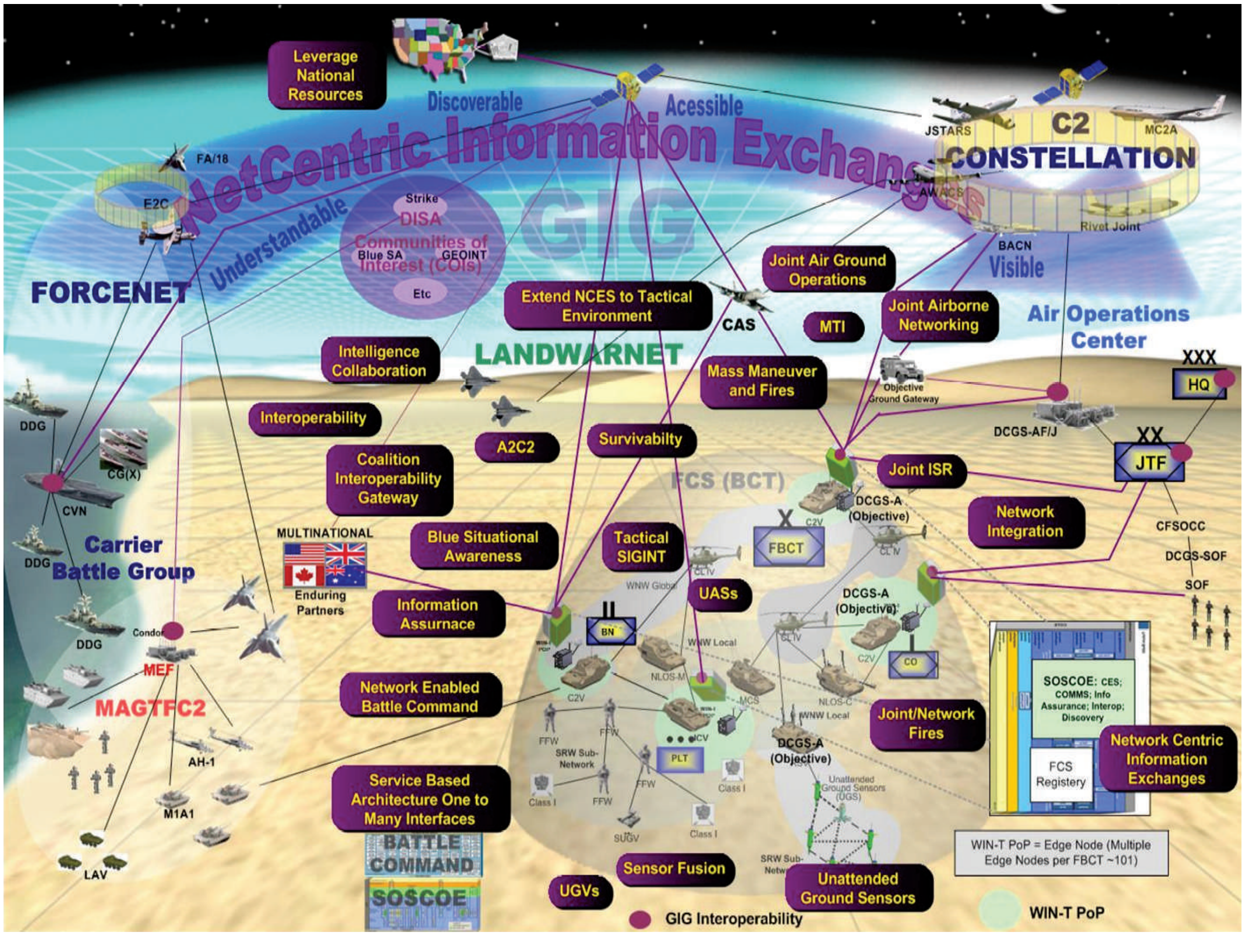

Figure 4. The DoD GIG's NetCentric Information Exchange Environment.

service layers to automate many of the functions currently done by soldiers over voice nets. *Figure 2* shows just that. Each capability has multiple steps, each step has multiple information requirements, and each information requirement is provided from a different source. In the current force these different sources could be information provided by separate staff sections; to enable this automation transition, the application and service layers are being built using a service-oriented architecture (SOA) so the software does the staff coordination, sometimes without human intervention. This software will operate while the host platforms are operating regardless of whether the host is static or mobile.

To complicate matters, to produce a safety release for a platform, testing must ensure the automated processes typically performed by the platform are conducted and that they operate correctly. This requires that testers ensure that the platform software and battle command software operate together safely, under specific conditions, within standards per the missions expected of the platform or system.

Testers and evaluators must place the network under test in a live-virtual-constructive mission environment and exercise the proper threads associated with the platform and its user with a common-measures framework. A common-measures framework enables testers and evaluators to understand what the correct tasks are and what data to collect, both for developmental testing as well as some operational testing.

System-of-systems testing (SoS)

SoS testing looks at a unit conducting a function of a military operation. The U.S. Army Training and Doctrine Command has written 25 integrated processes or unit level mission threads that combat brigades and below must be able to conduct to be effective. The FCS program has further refined these into 12 integrated functional capabilities that describe the specific actions that must take place to facilitate the functioning of a future force brigade combat team. Each of these processes is a set of complex mission threads that incorporates multiple vehicles and personnel executing multiple roles or tasks. To ensure that a family of systems is ready to conduct an operational test (e.g., limited user test or initial operational test and evaluation), developmental testing ensures that the mission threads operate correctly, and that the SOA applications and services operate correctly, beforehand. The development of a distributed testing capability is a key component to successful system-of-system testing because it enables systems in separate geographical locations to operate together as if they are on the same piece of terrain. An example of such a test actually executed by Joint Test and Evaluation Methodology project and FCS is depicted in *Figure 3*.

Joint network testing

System-of-systems testing enables the final strategy needed to test and evaluate systems for DoD, joint network testing. The end state that DoD is building toward is for all Services to become completely GIG compliant and all Services to be operating in one net-centric information exchange environment as shown in *Figure 4*. To enable joint network testing, it is critical that the Services become involved in joint efforts such as Joint Mission Environment Test Capability, Interoperability T&E Capability, the Joint Test and Evaluation Methodology, and the Army Air Expeditionary Force exercise. Services should actively seek opportunities to operate in large multisite exercises to better prepare for joint network test events. Involvement in these types of exercises enables the maintenance of a persistent test network capability and a current understanding of the evolving net-centric capabilities of acquisition programs. A persistent network is one that can be brought online when needed or one that operates 24 hours a day, 7 days a week, driven by test and evaluation requirements. A persistent network is more than hardware and software. It includes the personnel and their knowledge base to conduct distributed testing. *Figure 4* is a picture of where DoD is going and why services must come together and create a Joint Network testing capability to ensure that all network-enabled systems can operate on the DISA GIG.

Conclusion

DoD is transitioning to network-centric warfare. Programs are building network-enabled systems as part of that transition. The T&E community must transition as well. There are four strategies that the T&E community must embrace to transition to network-enabled T&E, and those strategies are PANN, capabilities-based testing, systems-of-systems testing, and joint network testing. If DoD is to test and evaluate the complex network-enabled systems they are building while meeting the net-ready key performance parameter and ensuring GIG compliance, these are the strategies that must be implemented. Testing and evaluating a platform and then checking the platform's communications systems separately will no longer ensure network-enabled systems are effective, suitable, and survivable. If DoD is to transition to network-centric warfare with network-enabled systems, the T&E community needs to transition as well. ❑

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Endnotes

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Addressing the Challenges of a Thruster-Based Precision Guided Mortar Munition With the Use of Embedded Telemetry Instrumentation

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This article describes advancements made with the use of embedded telemetry instrumentation with a digital signal processor and shows the large volume of information that is available during flight tests. Unique measurement capabilities and analytical techniques used to determine and understand the Precision Guided Mortar Munition flight behavior during the thruster-based guided maneuvers will be highlighted. Ways in which these data were used to make key decisions influencing the projectile's aerodynamic design and guidance, navigation, and control algorithms are discussed. These revisions resulted in a more stable airframe and more accurate maneuvers, as evidenced by several successful guide-to-hit demonstrations.

Key words: Mortar; munition; telemetry; aerodynamics; thruster.

The XM395 Precision Guided Mortar Munition (PGMM) is a multipurpose laser-guided 120-mm mortar round designed to defeat personnel under protective cover (behind earth or timber bunkers, behind masonry walls, or within lightly armored vehicles). The PGMM is being developed by the U.S. Army Office of the Product Manager for Mortar Systems (PM Mortars) for the U.S. Army Infantry Center (combat proponent). Alliant Techsystems (ATK, Plymouth, Minnesota) is the prime contractor. The U.S. Army Tank-Automotive and Armaments Command and the Armaments, Development, Research, and Engineering Center are providing technical support. The U.S. Army Research Laboratory (ARL) was tasked with developing an integral telemetry module (ITM) that fits within the round and can be used throughout the development, test, and evaluation process. The ITM provides an independent measure of truth for flight motion, structural characterization, and aerodynamic coefficient estimation from its on-board inertial sensors.

PGMM description

The PGMM is equipped with a semi-active laser (SAL) seeker to guide and maneuver to its intended target with the use of advanced guidance, navigation, and control (GNC) processors and a control thrust

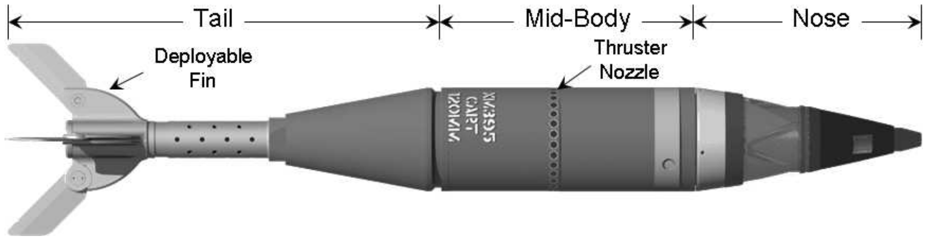

Figure 1. The XM395 Precision Guided Mortar Munition projectile flight configuration.

mechanism. The PGMM requires a human in the loop to designate the target and incorporates a blast fragmenting warhead with a variable delay fuze to provide high lethality against the intended target set. Designation is accomplished by any of the U.S. Department of Defense's laser designation devices (air, vehicle, or human transported). It will be compatible with all current and future 120-mm mortar systems. Its high accuracy will reduce collateral damage and decrease the logistics burden. After the fuze is programmed with time of flight, target type, and laser code of the day, it is fired much like any standard mortar cartridge via a five-zone charge system. The PGMM consists of three major assemblies (nose, mid-body, and tail) as shown in *Figure 1*.

Guided flight test program

Beginning in 2006, the PGMM program initiated a series of open-loop (preprogrammed) and closed loop (guide-to-hit) flight tests to characterize the projectile's performance and demonstrate its accuracy. During this guide-to-hit test campaign, the U.S. Army Office of the PM Mortars and ATK successfully demonstrated the world's first gun-launched, laser-guided mortar cartridge. One of the main contributors to its success was the timely, accurate, and thorough recording/transmission of in-flight performance information. This was made possible by the integration of a highly robust and reliable ITM. The ITM development was steered by a test and evaluation integrated product team providing inside knowledge of the schedule, technical issues, and test objectives.

ITM development and description

All flight-test rounds incorporated an ITM instrumentation system to collect and transmit on-board sensor and projectile mission data to a ground station for post-test analysis. The ITM (4.445 cm in diameter by 8.805 cm in length) provides an independent measure of truth for flight motion, structural characterization, and aerodynamic coefficient estimation from its on-board inertial sensors (see *Figure 2*). It also provides diagnostic information for ATK's on-board inertial sensors electronics unit, control thrust mechanism, warhead initiation module, SAL seeker, fuze function monitor, and flight thermal battery voltage monitor from the ITM's several input options (analog, digital, and low-speed and high-speed serial data). At the core of the ITM is a digital signal processor (DSP)–based telemetry system containing inertial sensor suite boards, a DSP encoder/formatter board, a transmitter board, and its own power supply. *Figure 3* shows the electrical block diagram of the ITM. The ITM's diagnostic functions for in-flight motion measurements are similar to those of other ARL telemetry systems (Davis et al., 2004; Wilson, Peregino, and Hall, 2006).

The ITM accommodates four channels of external analog input (0 to 5 volts direct current), 16 channels of external digital discrete input, and both low-speed and high-speed RS422 serial data input via two universal asynchronous receivers/transmitters. The asynchronous DSP encoder board enables reprogramming of the interfaces and telemetry frame format. The ITM has a 250-mW, S-band, phase-locked FM transmitter and uses a randomized non-return-to-zero-level (RNRZL-15) scheme. *Table 1* defines the various input and output of the ITM.

The ITM is installed into a portion of the warhead cavity located in the mid-body of the PGMM and

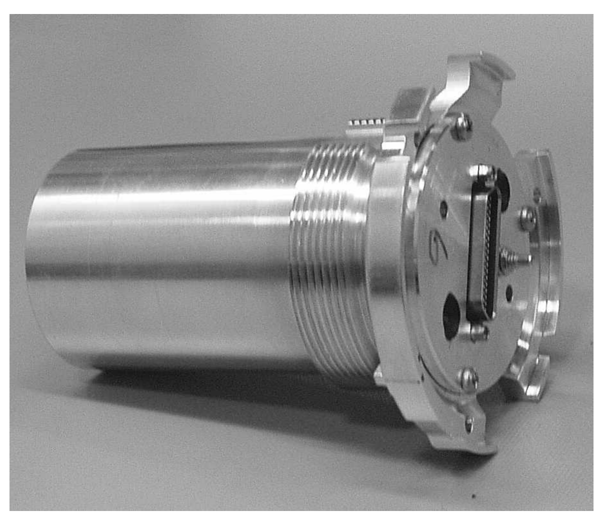

Figure 2. Integral telemetry module instrumentation package.

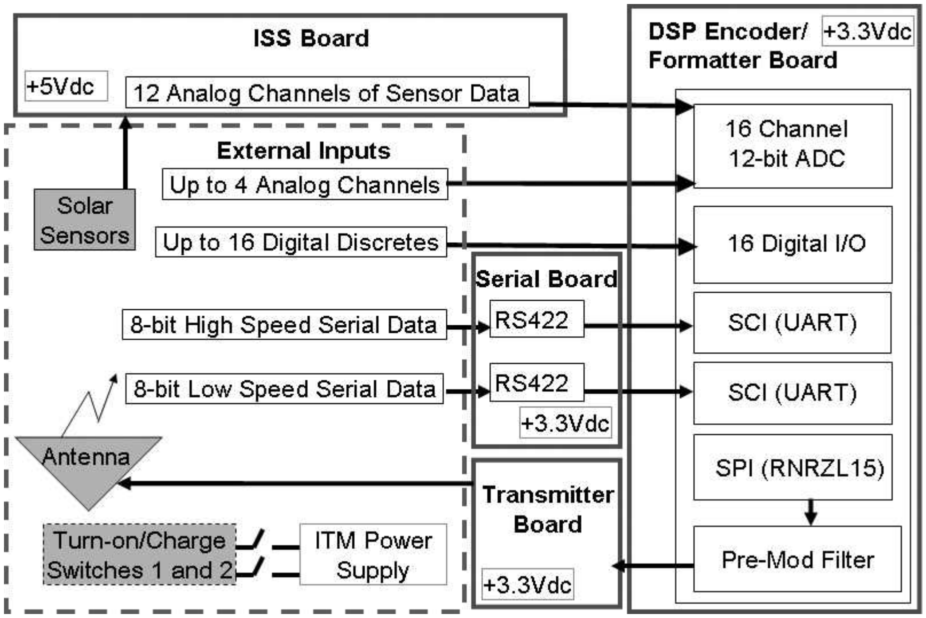

Figure 3. Integral telemetry module block diagram.

connects to a wrap-around antenna via a radio frequency (RF) connector. *Figure 4* shows the location of the ITM and associated PGMM subassemblies. A second connector enables an attachment to turn on switches, ARL solar likeness indicating transducer sensors, and various ATK input via a mating connector. The turn-on switches enable the ITM's batteries to be powered up externally. The ARL solar sensors are part of the inertial measurements and provide projectile roll rate and angular motion.

ITM data reduction

This section describes the data available from the flight tests, which demonstrate the extensive diagnostic capability of the ITM. The key aspects of each flight series were communicated with the ITM team to guide the output of quick-look data (available within minutes after a firing). This pretest planning was successful and enabled the PM Mortars to make quick, informed decisions about subsequent tests. Valuable test time and costs were saved because of this accurate, quick-look information.

All data are time stamped by the Inter-Range Instrumentation Group-B standard of time, and the time zero is referenced to the launch time. The data stream includes frame counter and subframe identifiers that verify any data losses. ITM battery voltage is monitored to ensure that it is above that required to power the ITM. Digital inputs from ATK hardware are monitored to determine the fuze status. ATK's

Table 1. Sensor, external analog, digital, and serial output

Measurement	Sampling	Range	Label
Solar field	16 KHz	0 to 5 V	Solarsonde
Axial acceleration along I	2 KHz	±50 g	Acc_I
Radial acceleration along J	2 KHz	±35 g	Acc_J
Radial acceleration along K	2 KHz	±35 g	Acc_K
Rate about I	2 KHz	±25 Hz	Acc_Ring
Magnetic field along I	2 KHz	±1.5 Gauss	Mag_I
Magnetic field along J	2 KHz	±1.5 Gauss	Mag_J
Magnetic field along K	2 KHz	±1.5 Gauss	Mag_K
Rate about J	2 KHz	±2000 deg/s	Rate_J
Rate about K	2 KHz	±2000 deg/s	Rate_K
Transmitter voltage	2 KHz	0 to 5 V	Bat_Mon
External analog inputs	2 KHz	0 to 5 V	ADC_R1 through ADC_R4
External digital inputs	2 KHz	0 to 3.3 V	Dig0 through Dig15
High-speed serial (HSS)	1.031 M	0 to 3.3 V	HSS
Low-speed serial (LSS)	38.4 K	0 to 3.3 V	LSS

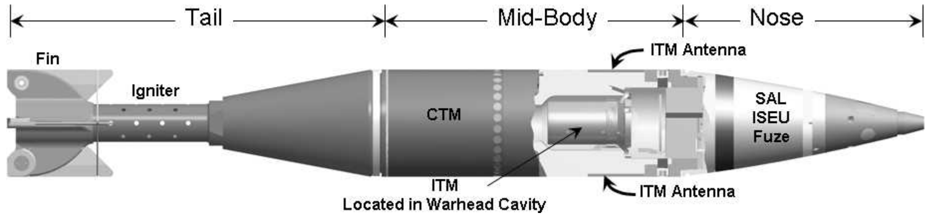

Figure 4. Precision Guided Mortar Munition guide-to-hit configuration with integral telemetry module parts located in the mid-body.

thermal battery voltage is monitored with one of the analog channels to verify that it is properly powered up. ATK's low-speed serial data, which contain the thruster commands (i.e., thruster number), and ATK's high-speed serial data, which contain the inertial sensors electronics unit and GNC solution output, are returned once they come online.

Several sensors within the ITM provide truth measurements. Accelerations (Acc_I, Acc_J, and Acc_K) from a triaxial constellation (I, J, and K body-fixed system) of low-g accelerometers are measured. Acc_I data provide axial acceleration data and detailed timing information during the drop, launch, and flight phases. Acc_J and Acc_K output provide radial acceleration during these phases, including detailed amplitude and timing information during thruster firings. All thrusters that were commanded by the control thrust mechanism can be verified by the low-speed serial data. Thruster firings can be observed in the accelerometer output. The accelerometer ring (Acc_Ring) is a constellation of accelerometers whose output is processed to obtain spin rate. Two rate sensors (Rate_J and Rate_K) provide a measurement of the body-fixed pitch and yaw angular rates. The root sum square (RSS) of Rate_J and Rate_K (RSS_Rate) gives the total angular rate. The processed solarsonde data provide roll rate (see *Figure 5*) and aspect angle relative to the sun. Similarly, the magnetometer output (Mag_I, Mag_J, and Mag_K) is processed to provide roll rate and aspect angle relative to the earth's magnetic field.

Additional ARL-developed processing can be used to determine the elevation and azimuth angles, namely, theta (θ) and psi (ψ). One technique requires two distinct planes of angular data (e.g., solar and magnetic) and transforms the motion in the earth-fixed system (Hepner and Harkins, 2001). Another technique integrates the pitch and yaw rate sensor data with respect to a known plane and then transforms these angles into the earth-fixed system. Theta and psi plots from this technique are shown in *Figures 6 and 7*. A θ versus ψ plot is shown for a short time interval covering one of the maneuver events (see *Figure 8*). Additional processing can be done to determine the body-fixed angles, alpha and beta.

Trajectory reconstruction and determining projectile aerodynamics

Additional processing can be done to fully reconstruct the trajectory and determine the aerodynamic coefficients. Both Extending Telemetry Reduction to Aerodynamic Coefficients and Trajectory Reconstruction (EXTRACTR) and TELA software packages have been used (Amoruso, 1996; Davis et al., 2005). Each combines telemetry data with radar data to fit the angular and positional data to a six-degrees-of-freedom equations-of-motion prediction of the test projectile trajectory. Telemetry data matched include rate sensors, solar and magnetometer aspect angles, roll rate, and accelerometer data. *Figure 9* illustrates a simulation match for one of the on-board rate sensors. This analysis has been done after each test to continually revise the aerodynamic database, enabling an accurate trajectory simulation of the projectile. *Figure 10* shows a revision of the aerodynamic database for pitching moment, $C_{M\alpha}$. The simulation is then used to perform trade studies, evaluate system performance, and aim the weapon during subsequent testing.

Thruster performance

The ITM's accelerometer measurements were used to evaluate the performance of the control thrusters. The accelerometers provided ample data to characterize the thruster firings, which typically lasted about

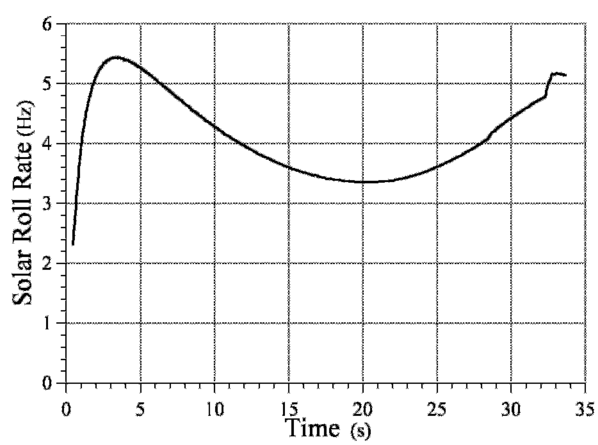

Figure 5. Solar roll rate versus time.

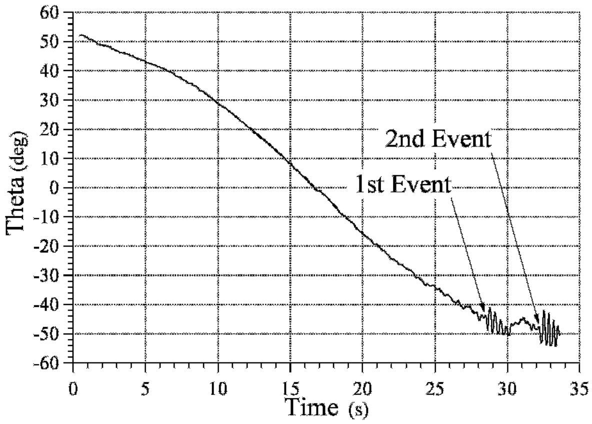

Figure 6. θ versus time.

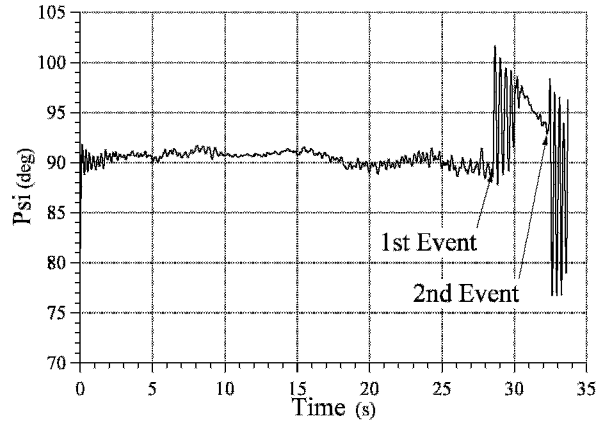

Figure 7. ψ versus time.

20 ms. We calculated the total acceleration of the body by taking the RSS of the lateral accelerations, as shown in *Figure 11* for a typical maneuver event in which six thrusters were fired in a group.

The accelerometer data clearly show the starting and ending time of each thruster firing. We converted the accelerations to forces by using the mass of the projectile and the total impulse applied to the projectile during each thruster firing (obtained by integrating the area under each curve). The thrust centroid (time to center of thrust) was also determined for each thruster firing. *Table 2* provides an example of the primary thruster data obtained or derived from the ITM, including thruster number, time of the thruster firing, and roll orientation of the initiated thruster nozzle relative to a reference frame (i.e., gravity, magnetic, or solar). The resulting body dynamics (roll, pitch, and yaw rate) at the thruster firing can also be measured. Precise knowledge of the impulse, thrust centroid, and projectile orientation is critically important for the projectile to accurately guide toward a target. The experimentally determined impulse and thrust centroid were used in the guidance algorithm for subsequent guide-to-hit shots.

Thrust angular alignment can also be determined with the use of ITM accelerometer data. Radial angular alignment is determined with the lateral acceleration components (Acc_J and Acc_K). The component impulse in the J and K directions can be calculated similarly to the method previously described to calculate the total impulse. Obtaining the J and K components of the impulse, one can then take the arctangent of the ratio of the impulses to determine the angular position of the impulse vector relative to the ITM. Relating this position to the known position of the thruster fired allows one to evaluate the radial alignment of the individual thruster. One can also obtain the axial thruster alignment in a similar manner. One can further obtain the axial alignment by taking the arctangent of the ratio of impulse in the I direction to the total impulse.

Jet interaction determination

When a lateral divert thruster is fired, the exhaust plume disturbs the flow field about the projectile. A high

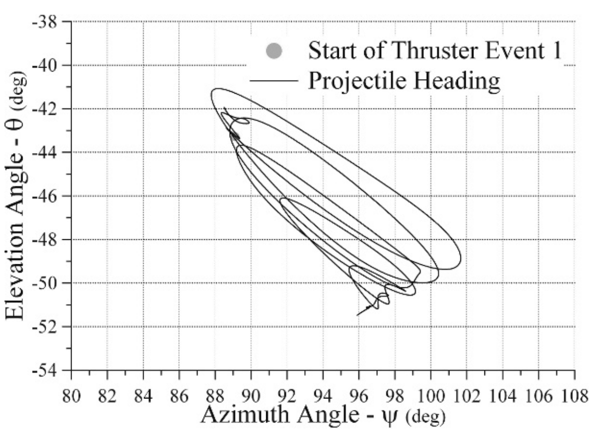

Figure 8. θ versus ψ after thruster Event 1.

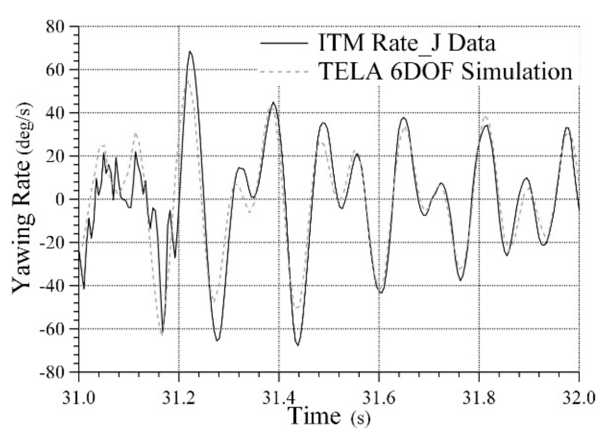

Figure 9. Trajectory reconstruction of rate data.

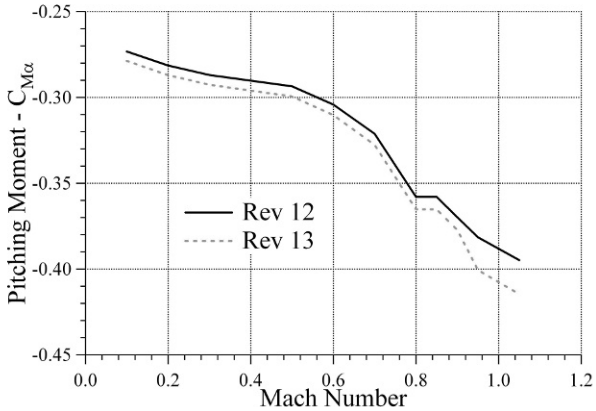

Figure 10. $C_{M\alpha}$ versus Mach.

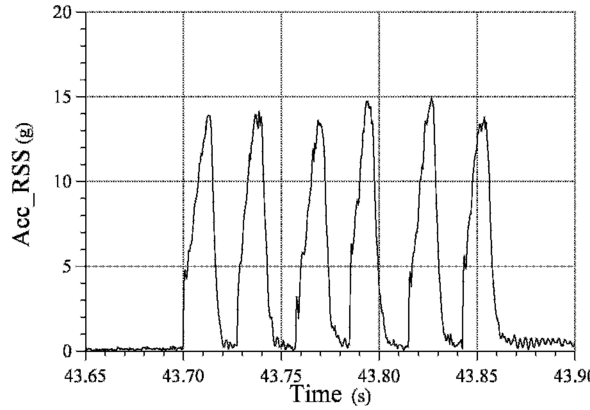

Figure 11. Root sum square of the lateral accelerations from thruster firings.

pressure region forms in front of the plume (where the free stream air slows as the plume is encountered), and a low pressure region is formed downstream from the jet. *Figure 12* shows the theoretical pressure field predicted by a computational fluid dynamics (CFD) code (Despirito, 2005). These pressures act asymmetrically on the body and are often referred to as the "jet interaction (JI)" effect. With the on-board measurements of thruster performance (from the accelerometers) and the angular response of the projectile (from the rate sensors), it is possible to estimate the JI.

To quantify the magnitude of the JI, an equation was derived to calculate the JI moment with known quantities for each shot and thruster event. The equation assumes that the angular rate measured by the on-board rate sensors is entirely attributable to two moments: the thrust force moment (from the nozzles not being located exactly at the center of gravity [c.g.]) and the JI moment. Additionally, it assumes that no aerodynamic forces or moments are contributing to the measured angular rates, and it treats each thruster event as one discrete event. If multiple diverters are fired in rapid succession and partially overlap, they are treated as a single event. The following equation defines the moment on the projectile attributable to JI:

$$M_{JI} = \left[I_Y * \dot{\varnothing} - I_T * X_T\right]/t \tag{1}$$

where M_{JI} is the moment attributable to JI (about the c.g.), I_Y is the transverse moment of inertia, $\dot{\varnothing}$ is the peak angular rate measured after divert event, I_T is total impulse delivered by divert thrusters, X_T is the location of nozzle relative to c.g., and t is the burn time of thrust event.

One may obtain the peak angular rate for each event by calculating the RSS of the two rate sensors measurements and plotting it versus time (see *Figure 13*). This plot corresponds to the event shown in *Figure 11*. The peak rate observed after the divert event is then obtained manually off the plot. This is an example of a well-behaved rate versus time plot, where the peak is evident and the residual motion is as expected.

It is possible to determine a nozzle location that will, in theory, produce a moment equal in magnitude but in the opposite direction of that caused by the JI moment (referred to as the optimum thruster nozzle location, $X_{T,O}$). The following equation can be derived by setting the angular rate to zero in the above equation and solving for the location term:

$$X_{T,O} = -\left[M_{JI} * t\right]/I_T \tag{2}$$

The optimum nozzle locations calculated with the methodology just given have been independently verified by a six-degrees-of-freedom trajectory simulation program. We do this by applying the measured thrust at the appropriate distance from the c.g. and

Table 2. Projectile thruster times and angles for the maneuver event

Thruster no.	Start time	End time	Burn time (ms)	Time to thrust centroid (ms)	Projectile roll orientation at thruster firing (deg)
1	43.6998	43.7195	19.7	10.42	322.29
2	43.7273	43.7460	18.7	9.18	329.11
3	43.7573	43.7780	20.7	10.65	316.18
4	43.7848	43.8035	18.7	8.67	321.78
5	43.8148	43.8335	18.7	9.63	327.45
6	43.8424	43.8615	19.1	9.20	321.12

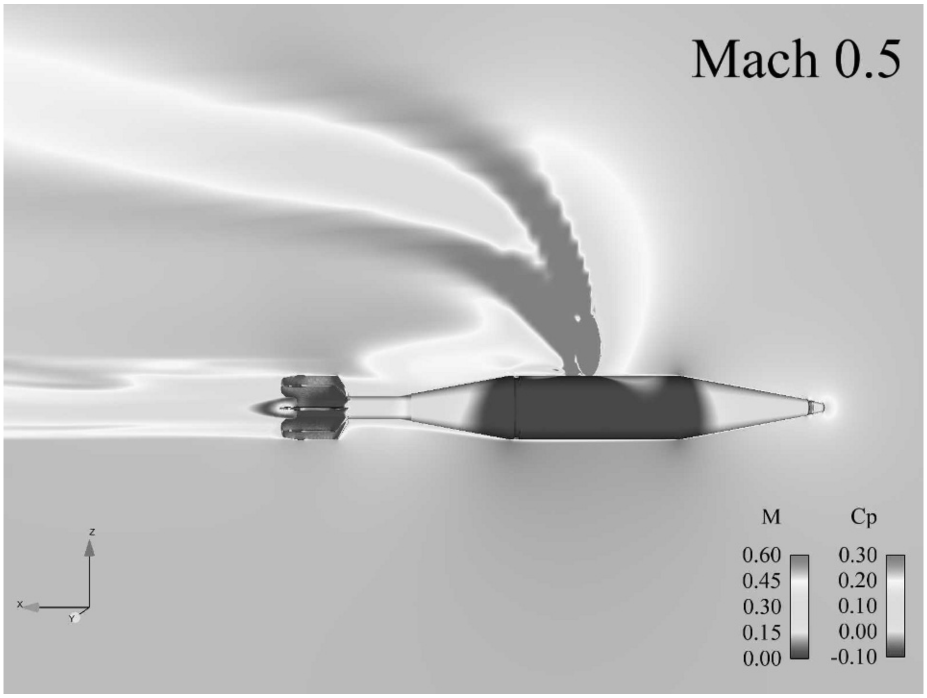

Figure 12. Simulated flow field during thruster firing.

verifying that the residual motion (angles, rates, etc.) matches the measured values. These results were very similar to those obtained from the CFD code.

Design iterations

During the development of the PGMM, there have been several changes in the projectile's exterior shape, fin type, and c.g. relative to the thruster location, as well as GNC algorithm changes. The thruster ring was originally located at the flight projectile's c.g., based on simulations of the early concept. During flight testing, it was found that the thrusters caused large yaw disturbances and the projectile had minimal yaw damping. CFD modeling helped determine that the large yaw

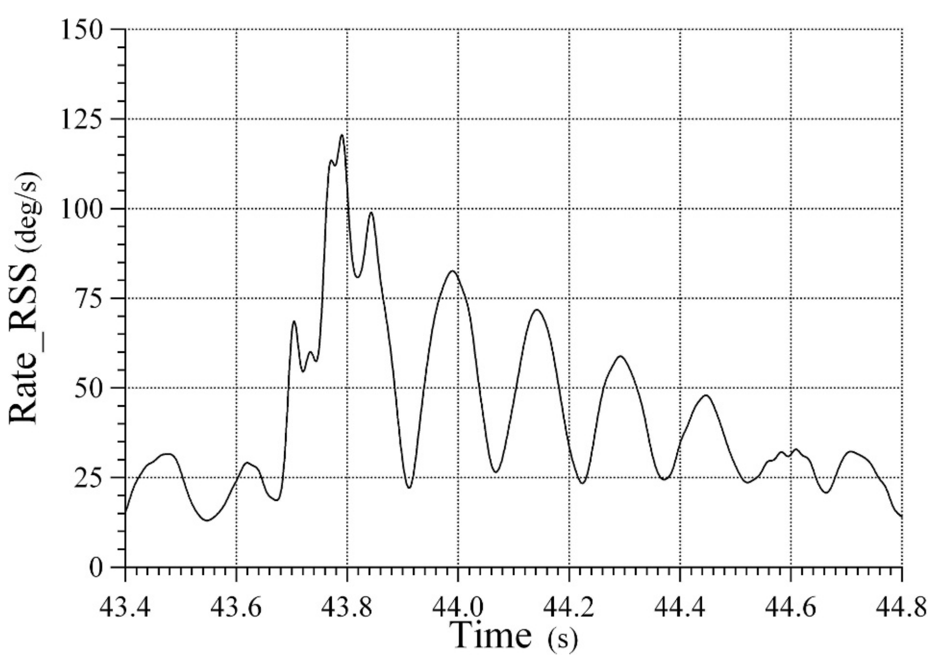

Figure 13. Root sum square of the angular rates from thruster firings.

disturbance was caused by JI. The data reduction methodology described in the previous section were used to identify an optimal thruster location relative to the projectile's c.g. The original fin design used subcaliber fixed fins. During the development, they were replaced by a super-caliber flip-back fin assembly shown in *Figure 1* for added stability and damping characteristics. Not only was the thruster design optimized for its desired impulse characteristics, but the time between successive thruster firings and the quantity of thruster firings required for a desired maneuver were determined from the numerous flight test data available.

Summary and conclusions

As of this report, the ITM has been successfully implemented on more than 30 PGMM flight tests. The ITMs have survived the high-g launch loads, transmitted clean/loss-free data to the ground, and provided a complete set of truth measurements and on-board diagnostics for each and every test. Quick-look data, available within minutes after the test, provided the necessary qualitative information to answer questions in the field regarding launch behavior, projectile stability in flight, proper thruster firing, and SAL acquisition. The data were made available to the test team, often before rounds had been marked for recovery by test ground personnel. This technical information, in concert with the photos and videos recorded by the test range, enabled the PM Mortars to make quick, informed decisions on subsequent test events. This reduced the cycle time for decision making from days to minutes, greatly reducing test costs and program schedule.

The processed data, available within days after the test, provided detailed quantitative information regarding the free-flight motion behavior (measurements of body orientation, yawing amplitude, and frequency), exact thruster timing (when the thrusters were commanded and when the body responded), and resulting projectile flight motion behavior after the thrusters were fired. This information was then used to determine airframe aerodynamics and to evaluate the GNC performance.

The telemetry system, data reduction, and processing techniques have provided a means to quickly, accurately, and fully understand what happened on board the projectile from launch through impact in multiple flight experiments. This information is not easily obtainable, if at all, from radar, video, or other ground-based instrumentation. The ITM data provided the necessary information leading to structural changes in the projectile's exterior shape, fin type, and c.g. relative to the thruster location, as well as GNC algorithm changes, which resulted in a more stable airframe and more accurate maneuvers, as evidenced by several successful guided-to-hit demonstrations. ❑

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A Collaborative International Approach to Store Separation

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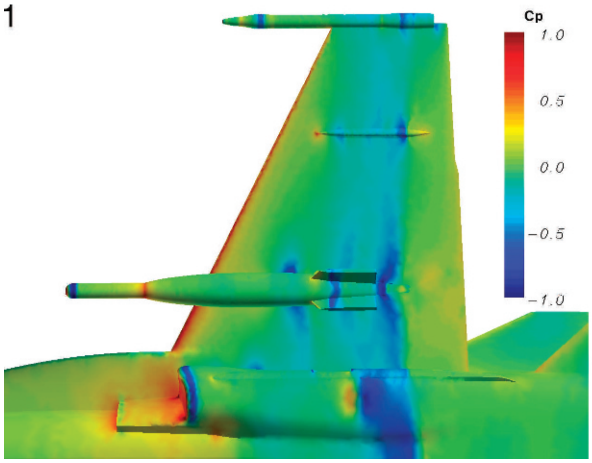
In 2005, in support of Northrop Grumman's efforts to market the Litening pod to the Australian and Canadian governments for use on their F/A-18A/B/C/D aircraft, Northrop Grumman contracted Naval Air Systems Command to support flight certification of the Litening pod and the associated pylon mounting system on station 4. The goal was to clear the GBU-12, GBU-38, MK-84, Dual AIM-120s, and FPU-8 fuel tank adjacent to a Litening pod on station 4 to the present TACMAN limits (with an adjacent advanced targeting forward looking infrared). Before the Litening pod effort, the Navy had two choices to clear new aircraft/store configurations: wind tunnel test or the build up approach (also known as hit or miss method). Both of these methods had serious limitations. Wind tunnel testing required at least 6 months of lead-time and a minimum of $500K. The build up approach consisted of increasing the release airspeed until the store came uncomfortably close to hitting the aircraft/adjacent stores. However, for quick turnaround, it was the only choice. This approach was not only very costly, but in some cases might have required a flight clearance recommendation that was too conservative. During the same time frame, the Department of Defense High Performance Computing Modernization Program office funded a joint U.S. Air Force, Army, and Navy Institute for High Performance Computing Applications to Air Armament. The Institute provided the Navy with the capability of using computational fluid dynamics to provide flight clearance recommendations for the Litening pod in a timely and cost effective fashion.

Key words: Computational fluid dynamics; external store separation; military aircraft; targeting pods; wind tunnel tests.

Store trajectories are defined in the Aircraft Axis System, which has its origin at the store center of gravity at release. The origin is fixed with respect to the aircraft and thus translates along the current flight path at the freestream velocity. The axes rotate to maintain constant angular orientation with respect to the current flight path direction. Due to the F/A-18C/D aircraft symmetry, stations 3 and 4 (left side) are interchangeable with stations 7 and 6 (right side), respectively. All data shown are right wing justified (i.e., station 6).

Previous flight test experience on the F-18C aircraft demonstrated that targeting pods mounted on station 4 could have a significant impact on the trajectories of stores from station 3 (Carron 2003). Recently (Benmeddour et al. 2006), Canada has used computational fluid dynamics (CFD) and wind tunnel testing to show



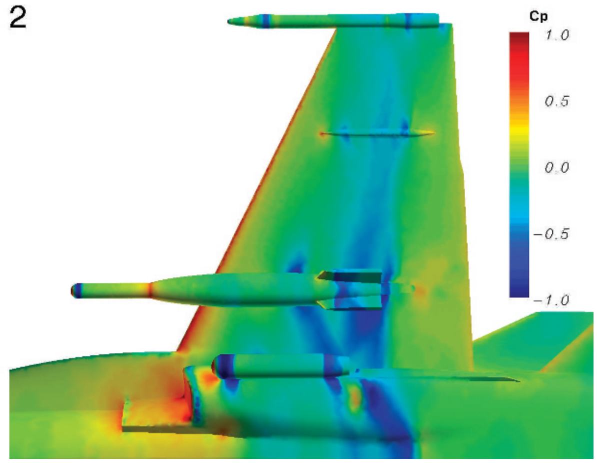


Figure 1. Station 4 clean. Figure 2. Station 4 targeting forward looking infrared.

that this effect was probably due to a transonic shock propagating from the targeting forward looking infrared to the tail of the store at station 3. This effect may be seen in *Figures 1 and 2*, which show the difference in pressure coefficient (*Cp*) distribution for the store at station 3 with and without the targeting forward looking infrared at station 4 at $M = 0.90$.

Because the Litening pod was expected to have a similar effect, Naval Air Systems Command (NAVAIR) established a team consisting of U.S. Navy, U.S. Air Force, Australian Government, and Grumman personnel to determine the separation characteristics of stores adjacent to the Litening pod.

1. Under a separate Institute for High Performance Computing Applications to Air Armament project, the Air Force provided the Navy with the CFD code BEGGAR (Rizk and Ellison 2002) and the associated geometry files for the F/A-18C, GBU-12, GBU-31, GBU-38, MK-82, MK-83, MK-84, and FPU-8 stores. The GBU-12, GBU-31, GBU-38, MK-82, MK-83, MK-84, and FPU-8 were all cleared to their end points using BEGGAR CFD calculations.
2. The GBU-12 was the first case where the Navy used a CFD calculation to flight test a store at its transonic end point without the usual buildup approach. This was also the case for the MK-83 and FPU-8 fuel tank.
3. The MK-82 was the first time that the Navy cleared a store to its end point with no flight testing. This was also done for the AGM-65 and laser guided training rounds stores.
4. A newly developed Matrix Laboratory (MATLAB) tool was used to integrate the flight test telemetry results. This resulted in an excellent match with all the flight test releases, with most stores cleared to the tactical manual (TACMAN) end point in one or two flights.
5. Usually, both photogrammetric and telemetry data are used to determine safe separation. Due to the time constraints of the program, the photogrammetric data were not analyzed. The excellent match with pre-flight predictions achieved by the team convinced NAVAIR to bypass the customary photogrammetrics analyses.

The results described above were based on CFD analyses, and have been described in detail in Cenko (2006, 2006), Cenko et al (2007), and Hallberg and Cenko (2007). This article describes work that has been performed since and concentrates on the stores where wind tunnel testing was deemed necessary.

Discussion

Because of cost and time constraints, the Litening pod effort could not use wind tunnel testing to clear all the desired configurations. Fortunately, the Institute for High Performance Computing Applications to Air Armamen had demonstrated (Cenko 2006) that CFD could be used to replace the wind tunnel for store separation purposes. It was therefore decided that CFD would be used to the maximum extent for this program. To date, eight stores have been cleared to their TACMAN limits using this approach, at an estimated cost savings (Cenko et al. 2007) of more than $1,500,000. An example of the correlation between the CFD predictions and flight test results may be seen for the FPU-8 fuel tank separating from the F-18C station 7 in *Figures 3 and 4*.

The eight stores that were cleared using CFD alone, and which probably represent the applicability limit of

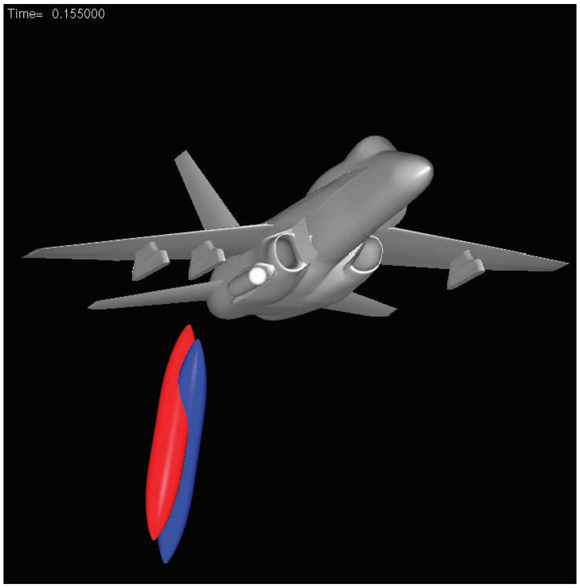


Figure 3. Fuel tank trajectory at M = *0.95.*

CFD, had several characteristics that made the approach possible. The hierarchy of store separation difficulty, in decreasing order, can be described as follows:

1. new store on new aircraft,
2. existing store on new aircraft,
3. new store on existing aircraft,
4. existing store on existing aircraft (new configuration),
5. existing store on modified aircraft (previously cleared configuration).

All the examples shown fell in the last category. The reason that CFD was a practical alternative was that there existed substantial wind tunnel and flight test

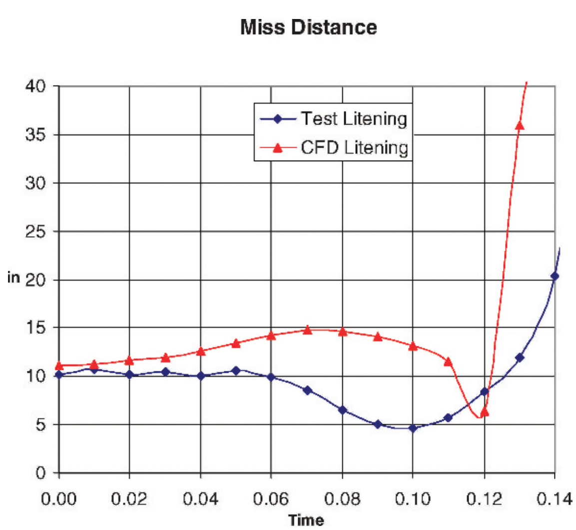


Figure 4. Fuel tank miss distance at M = *0.95.*

Figure 5. Dual AIM-120 at carriage.

data for both the F/A-18C/D aircraft and the stores that were tested. Because the aircraft modification only affected one station, it was reasonable to calculate the incremental effects using CFD. For cases where large amounts of test data are required, the wind tunnel has no match at the present time.

Even when all these conditions are met, the need for wind tunnel testing has not been eliminated. Because analysis indicated that the Dual AIM-120 configuration might represent a flight safety risk, the Defence Science and Technology Organization (DSTO) in Melbourne, Australia, conducted a wind tunnel test of the configuration. This is the first case where the Navy conducted a store separation wind tunnel test where the aircraft was mounted on its plane of symmetry. Analysis also indicated that the GBU-32, GBU-38, as well as their dumb bomb variants, would have trouble separating from the BRU-55 (CVER, multiple bomb) rack on station 3. Testing in the DSTO tunnel is planned for these configurations.

Dual AIM-120 configuration

As may be seen in *Figure 5*, the Dual AIM-120 assembly has very little clearance between the inboard fin and the Litening pod air intake. For this reason, a store separation wind tunnel test was required before any flight clearance. As Australia was at that time testing their F-18C configuration in the DSTO 0.8-m wind tunnel, it was decided to conduct this test in Australia. This reduced the cost to the program by more than a factor of two.

DSTO 0.8 meter transonic wind tunnel

The DSTO 0.8-m transonic wind tunnel was constructed in the late 1990s, and it became operational in March 2000. It is a closed-circuit continuous flow tunnel with a two-stage axial flow compressor powered by a 5.3 MW variable speed electric motor. The tunnel operates in the transonic speed regime from a Mach number of 0.3 to 1.2 in a continuously variable mode and Mach 1.4 with a fixed nozzle. It can be pressurized to 200 kPa absolute or depressurized to 30 kPa absolute using a plenum evacuation system, which has a single-stage centrifugal compressor driven by a 2.6 MW induction motor giving evacuation flow rates from the 3.1 m diameter plenum of up to five percent of the circuit air mass flow. Two ULVAC type PKS 060 oil rotary vacuum pumps are used for fine control at pressures below atmospheric. The Reynolds number ranges from 3×10^6 per m at 50 kPa and Mach 0.3, to 28×10^6 per m at 200 kPa and Mach 1.0. The test section is 0.81 m wide, 0.81 m high, and 2.7 m long, with slotted (six slots/wall) and solid interchangeable sidewalls, and a slotted floor and ceiling. The tunnel is equipped with a water cooled heat exchanger, air driers, and screens.

The tunnel has three model support systems: a vertical strut pitch-roll model support used mainly for free-stream tests, a sidewall model support (485-mm-diameter turntable in the solid sidewall) used mainly to mount centerline or half-models for use as the parent aircraft in stores tests, and a six degree-of-freedom store model support to move a store in the vicinity of the centerline model. The store support has a roll drive, a pitch drive, two independent yaw drives ("double yaw" system), and an axial drive. It is mounted on the port side of the vertical strut of the main model support, and it utilizes the vertical motion of this strut to move a store model independently of a model on the sidewall support. The model supports are operated remotely via the control and data acquisition system to provide accurate location and orientation of a model during a test.

A control and data acquisition system controls and monitors all tunnel operations, test parameters, and model support movements. All systems are started, controlled, and stopped from an operator console using touch screens and a keyboard. The tunnel can be operated in an "automatic" mode that steps through a test program automatically, or it can be operated in a single step "manual" mode. Data can be acquired and displayed in near real time.

F-18C and Dual AIM-120 wind tunnel model geometry

The tests were carried out using nine percent scale models of the F-18C aircraft, the AIM-120 missiles and their racks, and the Litening AT pod. All models were built to a tolerance of ±0.2 mm, and model surfaces were polished. The AIM-120 missiles were mounted on LAU127 racks (Dual AIM 120/LAU127 assembly), which, in turn, were mounted on a LAU115 rack. The F-18C model was made mainly from high strength aluminum with some stainless steel fittings and flow-through inlet ducts. The wing leading and trailing edge flap angles can be changed via servo motors or fixed at preset angles.

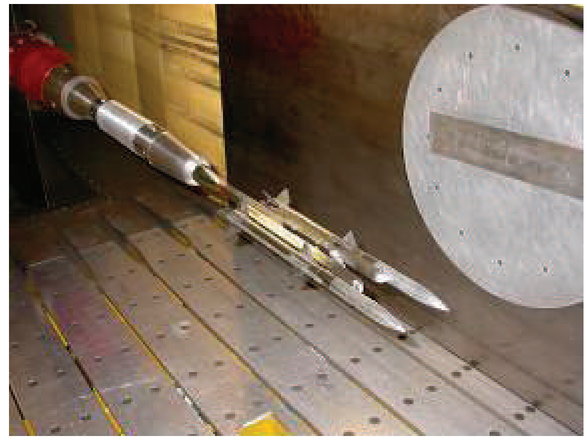


Figure 6. Dual AIM-120 assembly on pitch-roll rig.

Freestream tests were carried out with the Dual AIM 120/LAU127 assembly mounted on a six-component strain gauge balance and sting attached to the main pitch/roll rig as shown in *Figure 6*.

The Dual AIM-120/LAU127 grid tests were carried out with the same assembly mounted on the strain gauge balance and sting attached to the six degree-of-freedom store support system. *Figure 5* shows this assembly close to the LAU115 rack on the F-18C half model fitted with the Litening AT pod attached to the sidewall turntable. The very small clearance between the aft upper port fin and the pod can be seen in this figure. The horizontal tail was not fitted during the grid tests because of the potential for store support sting fouling.

Dual AIM-120 freestream test results

Wind tunnel separation data were obtained using a 0.09 scale, the F-18C/D model, and associated store hardware described above. Freestream and aircraft proximity (grid) data were taken at the DSTO 0.8 m (2.62 feet) transonic wind tunnel in Melbourne, Australia, using the specially designed rig to hold the Dual AIM-120 configuration. Freestream data were obtained for the Dual AIM-120 at constant yaw angles at selected Mach number and angle of attack combinations. Grid data were obtained along vertical rays emanating from the store carriage point.

Because the Dual AIM-120 configuration could not use a conventional aft mounted sting, both store off and on wind tunnel freestream data were taken to determine the effects of the mounting system on the store characteristics. The store off results were subtracted from the store on data to represent the store alone freestream characteristics.

The freestream values for normal force coefficient (C_N) and pitching moment coefficient (C_m) appeared reasonable and matched previous results. However, there was a large discrepancy in side force coefficient (C_Y), rolling moment coefficient (C_l), and yawing moment coefficient (C_n) at zero sideslip angle (beta). Since the configuration is symmetric about the y axis, there should be no side force, rolling, and yawing moment for betas equal to zero. Apparently, the shroud mounting system used to correct for the sting effects affected these data. For this reason, a store sideslip sweep at zero store angle of attack was also taken.

The rolling moment variation with betas changed sign for yaw angles greater than +4 or less than −4 degrees. The normal force also departed from near zero for betas greater than 4 or less than −10 degrees. The behavior for the pitching and yawing moments is similar for sideslip angles greater than +4 or less than −6 degrees *(Figure 7)*.

Clearly, the store aerodynamic data are suspect for yaw angles exceeding 5 degrees. These can be attributed to the sting assembly that was used. However, since the Dual AIM-120 configuration would hit the Litening pod if the yaw angle exceeds 2 degrees in the first 0.15 seconds, this effect is not considered significant. These effects may better be seen in *Figure 8*, which is a carpet plot of the Dual AIM-120 freestream yawing moment.

Wind tunnel grid data

Since the DSTO F-18 wind tunnel model is mounted at its plane of symmetry on the tunnel wall, only the right side of the aircraft could be tested. Therefore, the Litening pod, which is mounted on station 4 on the aircraft, was mounted on station 6 on the model.

Forty-five Grid runs were taken for the Dual AIM-120 configuration at various Mach numbers, aircraft angles of attack (3, 6, and 9), and store attitudes (store pitch angle = 0, +10, −10; store yaw angle = 0, +6). Twelve runs were repeated for the Litening pod removed to determine the effects of the Litening pod on the store forces and moments.

As may be seen in *Figure 9*, the Litening pod causes a large increase in nose down pitching moment and a small increase in yawing moment close to carriage. The normal force, side force, and rolling moment are not significantly affected *(Figure 10)*. Note that none of the coefficients except for side force approach zero at the furthest point away from carriage (11 feet full scale). Clearly, the last grid point still feels the effects of the aircraft flow field.

Trajectory simulations

The principal reason for acquiring freestream and grid data is to conduct offline trajectory simulations. As a first step in validating the wind tunnel data, flight test trajectories are compared with the trajectory simulations for the same conditions. Flight test data existed for M = 0.82 at 5,000 feet for the F-18C aircraft with AIM-7 instead of Litening pod on station 6. Wind tunnel and CFD predictions have demonstrated (Benmeddour et al. 2006) that the effects of the AIM-7 on station 6 are similar to the station being empty. The Navy generalized separation package, NAVSEP (Ray in press), was used to predict the trajectories released from station 7 using the grid data without the Litening pod. As may be seen in *Figure 11*, the predicted trajectory displacements are in excellent agreement with the flight test data for this case. The predicted pitch attitudes are also in excellent agreement *(Figure 12)*, whereas the yaw attitude is slightly underpredicted and the roll overpredicted.

Because the grid and freestream predictions give a good match to the clean F-18 flight test data, we can use the NAVSEP code to determine what the effects of the Litening pod would be on the Dual AIM-120 trajectory. As may be seen in *Figure 14*, there is a considerable difference between the predicted pitch, yaw, and roll attitudes for adjacent Litening pod and the flight test data for the aircraft with the AIM-7 on station 6.

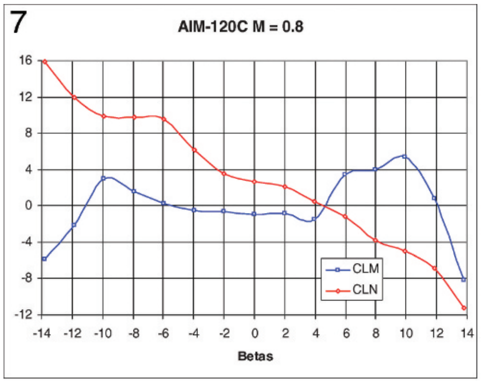
Miss distances

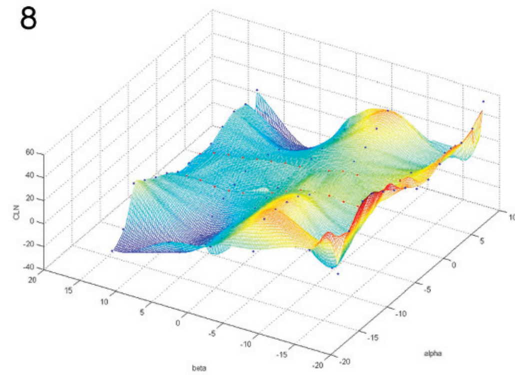
The miss distances for the Dual AIM-120 next to the AIM-7 flight test at M = 0.82 is shown in *Figure 15*. This distance is calculated using the clean station 6 grid data *(Figures 11 and 12)*. The other miss distance is that for the predicted Litening pod configuration *(Figures 13 and 14)*.

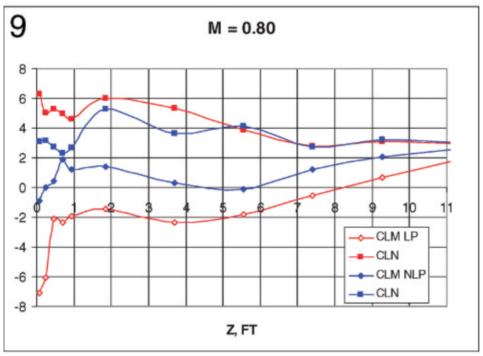
It appears that the presence of the Litening pod on station 6 makes little difference in the miss distance, even though it had a large influence on the pitch, yaw, and roll attitudes. The reason for this is that the increased roll is favorable, as it tends to move the tail surface away from the Litening pod. The miss distance decreases only when the Dual AIM-120 configuration is well below the Litening pod.

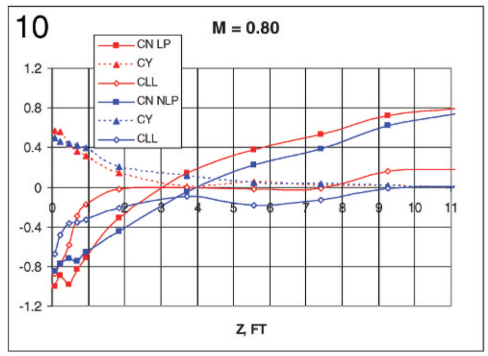
Flight test considerations

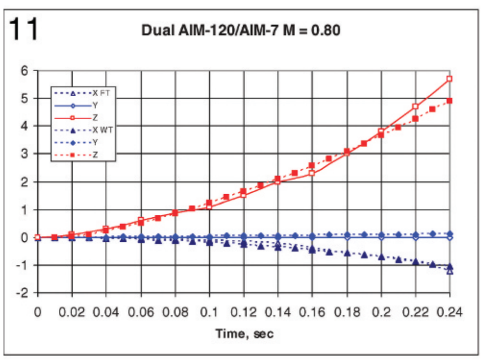
All of the trajectory simulations conducted offline after the test indicate that the Dual AIM-120 configuration should be able to separate safely from the F-18C aircraft with adjacent Litening pod.

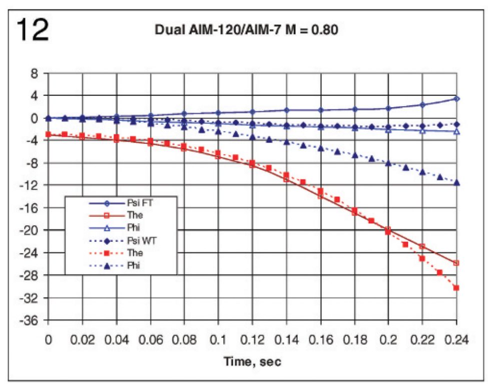


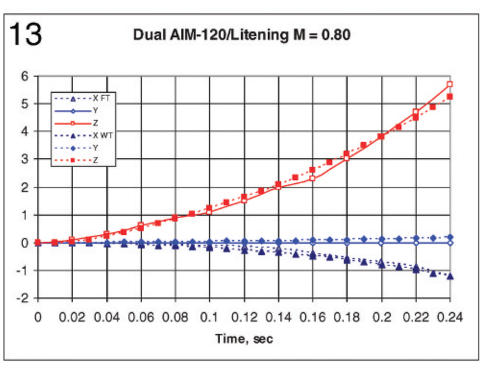












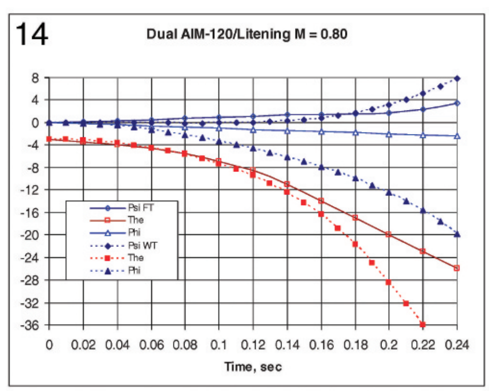


Figure 7. Dual AIM-120 freestream data. Figure 8. Dual AIM-120 freestream carpet plot. Figure 9. Dual AIM-120 CLM and CLN grid data. Figure 10. Dual AIM-120 CN, CY, and CLL grid data. Figure 11. Dual AIM-120 Displacement Station 3 clean. Figure 12. Dual AIM-120 Attitude Station 3 clean. Figure 13. Dual AIM-120 Displacement Station 3. Figure 14. Dual AIM-120 Attitude Station 3.

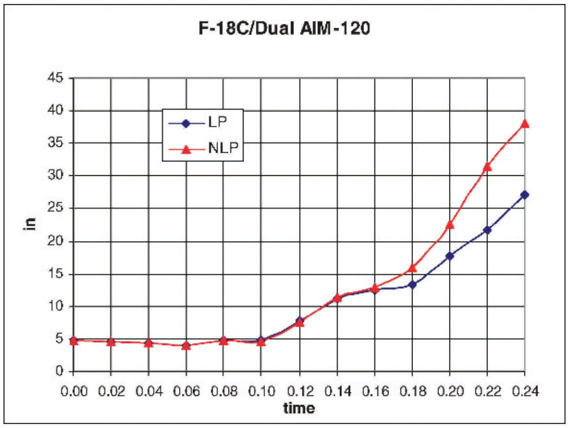


Figure 15. Litening pod effect on miss distance.

However, wind tunnel test predictions have been known to imperfectly (Cenko 2006) match flight test results. In particular, the test data are suspect for yaw angles in excess of 5 degrees, since the freestream data were inconsistent there. Because the grid data agreed with pretest CFD predictions *(Figure 16)* and parametric variation of the aerodynamic loads did not indicate any causes of concern, a flight test for this configuration is planned.

Conclusions

There are several organizations that promote national and international collaboration. The Institute for High Performance Computing Applications to Air Armament project provides an institute for the Air Force, Army, and Navy to share CFD tools and expertise between the U.S. Department of Defense and U.S. contractors. The Research and Technology Organization provides a similar mechanism for NATO participants, and The Technical Cooperative Program serves a similar role for English speaking countries. The American Institute of Aeronautics and Astronautics and International Test and Evaluation Association provide forums where this work can be presented.

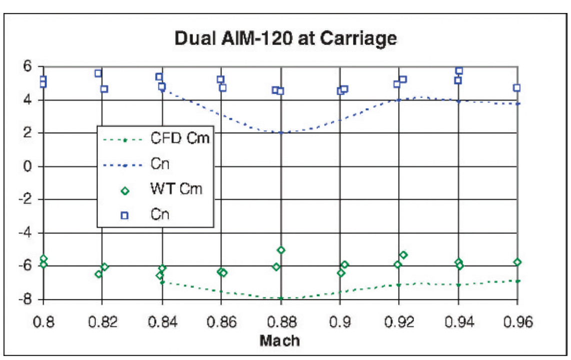


Figure 16. Wind tunnel and computational fluid dynamics moment comparison.

Collaboration, when properly structured, can have a synergistic effect on the process.

The F-18C/Litening pod integration benefited considerably from both the national and international collaboration involved. Because of the Institute for High Performance Computing Applications to Air Armament project, the Air Force provided the Navy with the CFD tools that enabled a cost effective and timesaving approach to the problem. Canadian wind tunnel test data enabled CFD tool validation, and testing in the Australian 0.8 m tunnel saved the program considerable time and money.

Clearly, collaboration is a win-win proposition for all the parties involved in store separation flight clearances. The laws of aerodynamics are the same for the Air Force and Navy, as well as overseas. Collaboration can avoid unnecessary duplication of effort, particularly for a common aircraft that has extensive use among U.S. allies (F-18 for the Navy and the F-15/16 for the Air Force). However, because of International Trafficking in Arms restrictions, international collaboration is becoming increasingly more challenging. ❑

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Computational Fluid Dynamics to Flight: Recent Success Stories of X-Plane Design to Flight Test at the NASA Dryden Flight Research Center

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Several examples from the past decade of success stories involving the design and flight test of three true X-planes are described: in particular, X-plane design techniques that relied heavily upon computational fluid dynamics (CFD). Three specific examples chosen from the author's personal experience are presented: the X-36 Tailless Fighter Agility Research Aircraft, the X-45A Unmanned Combat Air Vehicle, and, most recently, the X-48B Blended Wing Body Demonstrator Aircraft. An overview is presented of the uses of CFD analysis, comparisons and contrasts with wind tunnel testing, and information derived from the CFD analysis that directly related to successful flight test. Some lessons learned on the proper application, and misapplication, of CFD are illustrated. Finally, some highlights of the flight-test results of the three example X-planes are presented.

Key words: Computational fluid dynamics (CFD); flight test; model; super computer; wind tunnel; x-plane.

During the decade of the 1980s, the birth of the supercomputer and the enabled application of computational fluid dynamics (CFD) techniques both took off in a dedicated development effort within the aircraft research and design industry. In particular, the efforts of the National Aeronautics and Space Administration (NASA) in cultivating the development of both the supercomputer and CFD were unsurpassed. At the NASA Ames Research Center (Moffet Field, California), an entire division of the organization was dedicated to obtaining and operating what was at that time the state-of-the-art supercomputer, with another division of extremely talented individuals immersed in the development, application, and validation of CFD techniques. These early CFD algorithms were targeted for and made great use of the newly procured supercomputers working away in close proximity just across the parking lot. It was a productive, interdependent relationship. The gains made not only at Ames but across the country during that decade were unprecedented; one technology complementing and enabling the other.

Because of the tremendous increases in computing speed and memory storage that were occurring almost on a quarterly basis, the ambitions and abilities of the researchers grew at a rate to match. What took days or perhaps weeks to compute (and therefore was not undertaken as being impractical) in the late 1970s could be done in just several hours with the advent of the Cray-1 computer (Cray Research, Incorporated, Bloomington, Minnesota) in the 1981 timeframe. Once this computing speed became possible, the ability to increase the scope of the computations became available to the researchers, which then yielded CFD codes that required the next generation of supercomputer, and so on. Both computing speed and calculation fidelity involving ever-increasing fluid physics representations grew rapidly throughout the decade. Of interest, the newly-emerging computer architectures required new and unique ways of actually measuring their speed and throughput. It was obvious that computing power was increasing rapidly, but evaluating that power quantitatively required the development of a set of standardized benchmarks that could be uniformly applied to the new supercomputers, and tasked them in ways representative of the computational algorithms that were desired to be run in the day. The group at NASA Ames that was dedicated to obtaining and running the fastest computers available put together just such a set of benchmarks that measured, fairly and repeatedly, the power that was available to the researcher with each new generation of supercomputer operated at Ames (Bailey et al. 1991).

Background

In the early 1980s, CFD techniques were developed for calculation of flow fields about airfoils (2D) and wings (3D) using potential flow theory. Complex fluid physics including viscosity were neglected with this formulation. Nonetheless, very useful aerodynamic solutions were obtained within reasonable amounts of central processing unit (CPU) time. With the advent of true supercomputers such as the Cray-1s in 1981, the CPU time required for some 3D potential solutions became so small (in some cases just 10 seconds), a new possibility for CFD application emerged: performing computational design optimization. Toward that end, various researchers began looking at optimization algorithms and identified one method, the so-called quasi-Newton method, as a robust and general means of driving some objective function to a local (hopefully, global) minimum. Combining this optimization method with a fast CFD flow solver able to compute the lift-to-drag (L/D) ratio of a wing geometry in seconds or minutes of computer time rather than hours allowed the new supercomputers to not only analyze aerodynamics but alter the geometry to optimize them within some suitable constraints. One successful example of this optimization is given in Cosentino and Holst (1984).

As the transformational decade of the 1980s progressed, the trend toward faster processors, multiple processors, and more memory (speed) continued. Periodic upgrades of computing power could be counted on by the many researchers who were developing the complementary CFD algorithms for the new capability. The researchers, in turn, were then ready to challenge the capacity of the latest installed supercomputer to cope with these new, more complex algorithms. Increasing fidelity of fluid physics was modeled by the new CFD codes, surpassing the relatively simple panel and potential equation solutions with the nonviscous Euler equations of motion (adding vorticity effects) and finally, the full viscous Navier-Stokes equations. In parallel with the increasing fidelity of fluid physics came the increasing scope of geometry modeling. More and more dense 3D grids about complex geometries were created. Multiple body problems, internal flow problems, and even moving grids (store separation problems) were undertaken. Computational times of hours became the status quo; it seemed as though the problems undertaken were matched to the supercomputer capacity available at the time that would result in turnaround times of a few to several hours. It was as though this was the "threshold of pain" of the researchers and engineers for the time they could wait to see their answers. Complex problems requiring days were generally avoided, if for no other reason than it could not be reasonably assured that the computer would remain "up" for that length of time. A crash, reset, required maintenance, or reboot would cause such a long-running problem to be lost. Thus, a balance was struck between the computing power available, and the scope and ambition of the problem to be solved. As was stated, both areas enjoyed periodic "upgrades" throughout the decade.

Computational fluid dynamics and the aircraft design process

When starting with a "clean sheet of paper," the typical aircraft design process usually begins with a "configurator" laying out a rough sketch of the outer lines of the new shape on the computer aided design (CAD) system at hand. After the overall planform and other shaping characteristics are decided upon, the designer will usually have enough information to create a 3D model of the aircraft—a model suitable for early, lower-order CFD analysis. Efficient, flexible CFD tools including panel and potential equation codes and other linear methods are available and are extremely useful at this early stage of design to generate preliminary aerodynamics for the new shape. This information allows redesign and refinement to proceed quickly, maturing the aircraft design almost in real time.

At this point, there is sufficient detail in the CAD system to begin discretizing the shape and preparing the electronic model of the aircraft for more detailed and refined analysis, including both CFD and finite-element structural codes to be brought into the process. It is generally at this point that some state-of-the-art CFD methods are applied and detailed fluid dynamics are generated. Based on these results, further design refinement can occur, going back to the CAD model from which the original analysis was based. This iterative process can continue until the designers agree that the new aircraft shape meets initial criteria and performance characteristics and is worthy of still more complex analysis, to include building a model of the aircraft for wind-tunnel testing.

The author believes that it is at this point in the design process that CFD plays its most important role. Wind-tunnel models are generally very expensive, costing perhaps hundreds of thousands of dollars or even more. Wind-tunnel test time is a significant cost driver in a project. Viscous CFD methods applied to the candidate geometry before cutting metal for the model is generally time and effort extremely well spent. It can make, and has made, the difference between building a costly, disappointing model and one that simply verifies the adequacy of the design as predicted by the CFD methods. A "no surprises" wind-tunnel test is generally the goal at this stage of the design process.

As part of the wind-tunnel test/CFD analysis stage, CFD can provide a link from the model configuration and data to the actual aircraft configuration. To support the model in the wind-tunnel test section, a modification is generally made at the aft end of the shape to allow the wind-tunnel sting to be inserted in the rear of the model, which in turn is connected to the strain gage balance inside the model for force and moment resolution, and at the other end, affixed to the tunnel test section itself. The modification of the shape at the aft end of the model to accommodate the typically cylindrical sting is called the sting distortion. Obviously, the data taken are then for the shape with this distortion, not of the actual aircraft (undistorted shape). Computational fluid dynamics can provide a unique and generally quite accurate "sting distortion correction," allowing the designers to correlate, using this correction, the forces and moments measured in the tunnel to what they would be on the actual, undistorted aircraft shape. In fact, one way to accomplish this is to model the aircraft shape in CFD with a perfectly expanded jet plume shape emanating from what would be the engine nozzle, which should give the forces and moments on the actual aircraft shape as it would be in flight with the engine plume. The aerodynamics of this shape can then be correlated to the wind tunnel measurements, which represent a distorted body shape and a cylindrical solid plume (sting). As a double check, one can also model this sting/distortion shape in CFD, giving all of the increments for correlation and prediction of actual aircraft performance.

In addition to forces and moments, wind-tunnel models typically have several pressure orifices in order to measure the pressure distribution on the surface of the model. By their very nature, CFD solutions provide surface pressures everywhere on the surface of the model, limited only by the grid density (discretization) of the surface. Therefore, good correlations can be made between the surface pressure measurements at the few locations on the model, and the overall pressure distribution predicted by CFD. If the correlations are good, the designer can be relatively confident that the forces and moments predicted by CFD are good as well. If not, the wind-tunnel data can be used to calibrate or even improve the CFD method, by making improvements to the calculation method and/or grid density, and then having the solutions rerun.

The relationship of CFD and wind-tunnel testing is synergistic and complementary—they are not exclusionary. In the author's experience, the best use of CFD early in the aircraft design phase is twofold: first, it can assist the designer (and configurator) in shaping the aircraft in a preliminary way to meet early performance criteria; second, it can greatly aid in designing a wind-tunnel model that can be reasonably expected to perform well. Gross errors in design are usually predicted well enough by CFD to make corrections with confidence in the model design. Once commitment to a model design is made, and cutting the metal begins, CFD analysis can continue before entry into the wind tunnel to fill out the database of flow conditions for later reference once the wind-tunnel data begin to be generated. Indeed, it can be extremely useful to have the CFD-generated aerodynamic database available in the wind tunnel to correlate immediately with the data coming out of the test in real time. Once in the author's experience, wind-tunnel testing was stopped because the data did not at all correlate with the CFD predictions, and, in fact, an error in the wind-tunnel data reduction parameters was found and corrected. Without this capability, the tunnel testing and data acquisition would have continued with this error unnoticed, requiring a total recalculation of the tunnel database after the test (when the error, hopefully, would have been found).

Comparisons and contrasts with wind-tunnel data

Using CFD effectively in the manner described in the previous section, and upon detailed comparisons of the CFD predictions to the wind-tunnel data, several conclusions are generally evident. Assuming a robust and accurate Navier-Stokes flow solver (and sufficiently dense flow field grid) is used, typical strengths and weaknesses of the CFD analysis are brought forth. For flow conditions of low angle of attack and/or sideslip (benign flow with little or no separation), the CFD-predicted forces and moments as well as surface pressure distributions are usually found to be in good to very good correlation with the wind-tunnel data. Once a few conditions of this nature are checked, the CFD method can be used with good confidence for examining the flow field in detail, perhaps with an eye toward minor redesign of the shape. These correlations can help tremendously in taking the design further along the path to a prototype aircraft post-wind-tunnel test. Because the CFD analysis was found to be in good agreement with the wind-tunnel data at these benign conditions, one could conclude it might be safe to trust the method to aid in refining the shape further, without, perhaps, building a new wind-tunnel model and retesting. This therefore saves a step—an expensive and time-consuming one—for the next iteration of the design process.

Another benefit of CFD analysis, for these benign flow conditions, would be to extract the increment to the results of the sting distortion mentioned earlier. The overall predicted L/D ratio of the design will be altered in the wind-tunnel data due to the presence of the sting and the attendant distortion of the aft section of the aircraft. Computational fluid dynamics analysis of the undistorted shape will produce the increment of this alteration in performance. Thus, the wind-tunnel data, with CFD-generated corrections, can be recalculated to better represent the aircraft design in flight. This is routinely done for aircraft configurations, especially those in which the sting is inserted at the aft end (engine nozzle end) of the aircraft. It is an extremely useful correction technique.

The success with which CFD can be compared with wind-tunnel data is usually confined to the benign flow conditions of small-to-moderate angle of attack. For the higher transonic Mach numbers, where strong shocks are prominent on the aircraft shape, the ability of CFD to cope with and accurately predict flow field separation, shock-induced separation, or massive flow separation at very high angles of attack is limited at best. Highly viscous-dominated flow conditions, wherein many simplifying assumptions used in formulating CFD codes are not valid, create the limitations evidenced upon comparing both the forces and moments and the surface pressures to the wind-tunnel data. What is generally found is that, for example, the lift curve slope of the aircraft configuration is followed quite well over the small-to-moderate angle of attack range. Above this range, near the onset of lift breakdown, the slope generated by the CFD methods will diverge from the data. The CFD methods can still give an approximation of where the lift curve "knee" will appear but likely will not be very accurate in the calculation of maximum lift coefficient (CL_{max}), for example. It may also be found that upon looking at the surface pressure distributions, the shock location, strength, and sharpness will be inaccurate. The stronger the shock waves, generally, the poorer the CFD calculations of their strength will be. Specifically, over the range of approximately Mach numbers 0.90 to 1.10, the strength of the shocks and their ability to separate the boundary layer are difficult for CFD methods to model accurately. If the Mach numbers are increased to, for instance, 1.2 and above, however, then the calculations again become more accurate in terms of forces and moments and surface pressure distribution predictions.

Drag calculation is another general area of CFD weakness. Since the drag is usually, for most aircraft configurations, small when compared with the lift and moment forces, inaccuracies play a larger role in the values obtained. Also, since drag onset due to separation is largely a viscous-dominated flow characteristic, the extent of separation is difficult for CFD to compute well. This weakness will manifest itself when comparing drag polars of the configuration to the wind-tunnel data. It should be mentioned here that even for the benign flow conditions and lower angles of attack, the absolute drag computed by the CFD method may be "off" by an almost constant increment over the entire range of the data, diverging finally at the more severe conditions. This increment may come about from the difference between the calculated skin friction drag and the wind-tunnel data. The increment can sometimes be determined to be fairly constant at a given Mach number; therefore, upon examination of the data, it may be possible to "correct" this incremental difference by adding a constant to the CFD-calculated drag via post-processing of the computed data and then replotting the CFD results with the wind-tunnel data superimposed, effectively compensating for this incremental error in the absolute drag numbers.

Other major areas of comparison include the moment curves and the derivation of stability derivatives. Often, again for the more moderate flow conditions, these curves are fairly linear, and CFD can do a very good job of predicting these quantities. Asymmetrical calculations of a model at sideslip conditions in CFD require a full grid, without taking advantage of a symmetry plane. Therefore, these calculations double the time and computing resources required. Once comparisons with wind-tunnel data are made and found to be favorable, investing these resources to compute asymmetric stabilities derivatives becomes worthwhile.

Finally, surface pressure distributions are easily compared (if the wind-tunnel model is so equipped), and for flow conditions where good comparisons exist, the CFD pressures can then be used for other detailed analyses of the configuration. For example, the dense surface pressure data can be used in conjunction with a finite-element structural model for calculation of loads and moments about the aircraft.

Lastly, as was mentioned earlier, the all-important calibration of the sting distortion increment is usefully provided by CFD methods. It allows extrapolation of the characteristics of the wind-tunnel model (with sting distortion) to the actual aircraft configuration with the correct aft shaping. This correction makes the wind-tunnel data even more useful for prediction of full-scale aircraft performance parameters.

Again, one of the best uses of CFD is to ensure that the wind-tunnel model that is built yields a largely "no surprises" wind-tunnel test. Once the CFD methods are so calibrated from one test, it is possible to apply them with even greater confidence to the next design iteration, even perhaps allowing refinements to be made to the design without the need for a subsequent wind-tunnel reentry. This is clearly where investment in CFD pays dividends.

Difficult areas for application of computational fluid dynamics

The discussion in the previous section often referred to "benign or moderate" flow conditions. These conditions are typically the low-to-medium angles of attack (or sideslip), and the low transonic or lower supersonic Mach numbers. Once significant flow separation is present, or at high transonic Mach numbers (approximately 0.90 to 1.10), where very strong shocks are present, discrepancies with test data are likely to be prominent. In typical CFD codes used for full aircraft configuration analysis, turbulence is generally modeled to some approximation in order to provide a reasonably sized problem. The various turbulence models do a fairly good job for areas of no-to-small separated flow. Once the separation becomes significant, with large areas of stagnated and recirculating flow, these models generally break down. The result is the under- or overprediction of the separated regions, with the attendant inaccuracies in the surface pressure distribution and integrated forces and moments. Where very strong shocks are present, first the shock strength and location are usually poorly predicted, and then the resulting flow separation and recirculation regions are accordingly wrongly predicted. When applying CFD under these conditions, great caution should be taken unless there are test data to either validate the results, or to calibrate the errors of the computations.

Even under benign flow conditions, CFD can still be misleading when applied to certain regions of the aircraft shapes flow field. For example, applying CFD in a boattail region, perhaps in an aft-facing step area or in the area of the exhaust nozzle, significant flow separation can exist even for benign flow conditions. Drag calculations for a configuration with aft-facing steps will likely be inaccurate. Configurations with landing gear in the flow stream are similarly troublesome. Landing gear are often complex shapes, both difficult to model in the computational grid, and difficult to compute for the CFD flow solver. It is often desired to evaluate the increment of drag with landing gear down versus landing gear retracted, and thus the temptation to use CFD methods to evaluate this early in the design stage. Again, caution should be exercised in these areas of interest unless wind-tunnel data are available to calibrate and correct the results.

Application of computational fluid dynamics to internal flows

Most of the discussion thus far has been made in the context of CFD analysis of the external shape of an aircraft configuration, for the purposes of force and moment calculation and surface pressure distribution. Computational fluid dynamics can be and has been applied very effectively to the calculation of internal flows, specifically the calculation of inlet and nozzle flows including the ducting before and aft of a simulated engine. In fact, many more detailed wind-tunnel models have provision for so-called "flow-through" configurations, wherein an inlet is uncovered and flow is allowed to enter the inlet, flow through the model, and exit at the aft end of the model near the sting area. To control the flow through this ducting, different inserts can be fabricated to choke down the flow at the exit, thus giving the effects of varying mass flow. To correctly compute the flow about (and through) such a model, it is necessary to grid and model the internal flow, including the effects of varying mass flow. This method allows calculation and prediction of inlet drag and inlet spill. These effects clearly show up in the surface pressures near and immediately behind the inlet, and of course affect the drag and base pressures near the sting. Including these in the CFD model can greatly improve the agreement of the computations with the wind-tunnel data. In fact, if the CFD analysis is seriously used in the detailed design of the wind-tunnel model, these effects should be included.

In addition to flow-through models, purely propulsion-related internal flows can also be effectively computed. Inlet and ducting designs can be fairly accurately assessed provided the attendant flow separations are reasonably subdued. Won et al. (1996) outline some detailed internal flow calculations and their comparisons with experimental data. Similarly, nozzle flow paths can be designed using internal CFD computations with care toward and knowledge of the inherent limitations. These are generally more complex flow problems than purely external calculations, yet very good results can be obtained that aid greatly the designer's efforts to refine a configuration before committing it to costly metal fabrication and testing.

Figure 1. The X-36 Tailless Fighter Agility Research Aircraft in flight over the Mojave Desert. Photograph is provided by the NASA Dryden Flight Research Center photo collection.

Figure 2. The X-36 Tailless Fighter Agility Research Aircraft in flight.

In addition, CFD analysis can help direct where wind-tunnel model instrumentation (e.g., pressure taps) should be placed on the surface for the best results.

Computational fluid dynamics analysis yields results directly applicable to flight test success

The process of applying CFD analysis to aircraft design in the manner illustrated above, with all of its limitations, has been instrumental in first allowing a well-performing wind-tunnel model to be built, and second, in allowing the extrapolation of both computed and measured quantities to full-scale flight test articles. Many of the corrections to wind-tunnel data, extrapolation of wind-tunnel data, and modeling of physical features of an actual aircraft can play a major role in ensuring flight test success. Often, the X-plane aircraft design will undergo many design changes after the wind-tunnel model (and its testing) is completed. These may be minor changes, but nevertheless some quantification of the effect on aerodynamics and/or performance must be made in order to develop the flight control software. Computational fluid dynamics analysis, especially after having been compared (and somewhat calibrated) with the wind-tunnel test data, can be confidently used in assessing these changes to the flight article and the increments used to modify the database for inclusion into the flight control law development. This analysis and subsequent database update was done repeatedly during the design and testing process for each of the three X-plane examples given in this paper, and the flight test results reflect the benefits of such an approach. In short, the CFD corrections, when properly applied where they are valid, can be more accurate than simple extrapolation. In particular, stability derivatives can be computed from the CFD forces and moments, and over the regions of validity (benign-to-moderate flow conditions), have been found to be quite accurate during flight test. For neutrally to highly unstable aircraft configurations, accurate calculation of these stability derivatives is critical.

X-36

First of the three examples cited in this article, the X-36 design, followed the path described herein almost exactly and was the author's first end-to-end success story of CFD-to-flight. The X-36 was a tailless fighter agility demonstrator aircraft that proved, both via full-scale simulation and subscale flight test, that it is possible to achieve fighter-class agility with a configuration without any vertical tail surfaces *(Figures 1 and 2)*. Yaw control was provided entirely by using split ailerons (drag rudders) and/or thrust vectoring. Extensive analysis was performed on both this and precursor (similar) configurations using the full spectrum of computational analysis tools available to the designer. Each of the various types of CFD methods were used at the appropriate time during the configuration development, and each refinement of the design was aided significantly by the CFD analysis performed. As the design matured, more sophisticated CFD methods were employed. Critical to this process was an assessment of the stability and control derivatives of the design, as instability was a given byproduct of the goals of the aircraft. Thus, candidate configurations were assessed using the various analytical methods that were applied in determining the levels of instability, making sure that they were tractable given the capabilities of the modern digital flight control systems of the day. Occasionally, the analysis tools showed levels of instability that could not be tolerated,

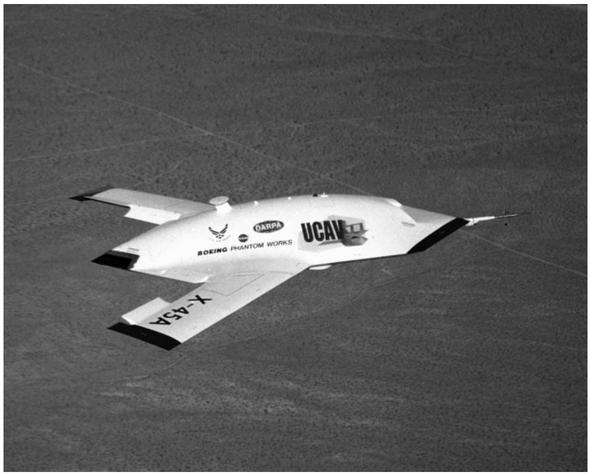

Figure 3. The X-45A Unmanned Combat Air Vehicle in flight over the Mojave Desert. Photograph provided by the NASA Dryden Flight Research Center photo collection. Photo by Jim Ross, taken December 19, 2002.[2]

and design adjustments had to be made to bring the configuration back to within the acceptable limits of stability and control.

Before designing the X-36 wind-tunnel model, extensive full Navier-Stokes CFD analysis was performed on the wind-tunnel configuration (including the sting distortion), again providing valuable data to fine-tune the shape and help locate instrumentation on the model. Once committed to metal, further extensive CFD runs were performed, pre-running many of the cases to be run in the wind tunnel, and producing a database similar to what was to be generated in the wind-tunnel testing. Therefore, when the actual data acquisition began in the tunnel, the CFD database was already in place for early comparisons with the data, almost in real-time as it came out of the tunnel data system. It was because of this advance preparation that an early error in the data reduction scheme in the wind-tunnel calibrations was found and corrected before too much time had passed.

As a result of the preliminary analysis using full Navier-Stokes CFD, the initial results of the wind-tunnel data indicated, as desired, "no surprises." This meant that the model designed was performing exactly as had been hoped, and as had been evident from the CFD database. Further, the piloted simulation of the aircraft, using the stability derivatives of the configuration as analyzed by CFD, not only was entirely flyable by the test pilot but also met the maneuverability and agility goals that were defined early in the program.

From the successes noted above, the decision was made to take the next step and actually build a subscale flyable prototype. This experimental aircraft would be remotely piloted from a fixed ground station and hand flown by the same pilots who evaluated the handling

Figure 4. The X-45A Unmanned Combat Air Vehicle in flight.

characteristics in the simulations performed earlier using the combination of CFD and wind-tunnel derived stability coefficients. The success of the flight test was exemplary, as the X-36 flew 33 safe and successful research flights from 1997 to 1998. An assessment of the success of the flight test and stability and control characteristics is found in Balough (1998).

X-45A unmanned combat air vehicle (UCAV)

The second example cited in this article is the X-45A UCAV. As can be seen in *Figures 3 and 4*, the X-45A followed in the footsteps of the X-36 in that it too was configured without any vertical control surfaces. In this case, oppositely deflected outboard elevons, in a so-called crow mix fashion, along with thrust vectoring, were used for yaw stability and control. The design evolution of the X-45A followed a very similar, if abbreviated, path of CFD analysis, design refinement, wind-tunnel model design, and finally flight article design and fabrication. Much of success of the X-36 approach to tailless, highly unstable configuration design and control led to another tremendously successful X-45A flight test program. No fewer than 64 safe and successful research flights were conducted on two X-45A demonstrators, some of which were dual-vehicle flights. Much more about the X-45A UCAV program and flight test can be found in Cosentino and Hirschberg (2004–2005) and Wise (2003).

X-48B blended wing body demonstrator

The third and final example cited in this article is the X-48B Blended Wing Body research aircraft *(Figures 5, 6, and 7)*. In this particular case, the configuration has been of interest and under investigation for more than 20 years. Extensive CFD analysis, encompassing all methods described in this article, has been used to establish and refine the aerodynamics of this unique configuration. Until just recently, no actual flight test data had been obtained. The X-48B

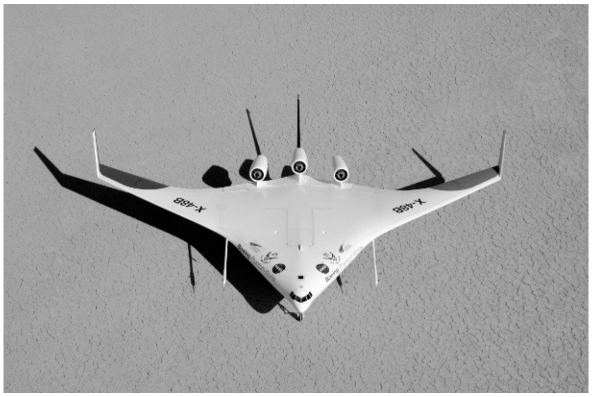

Figure 5. The X-48B Blended Wing Body research aircraft at rest on the Rogers Dry Lake bed.

Figure 6. The X-48B on its first flight over the Dryden/Edwards flight-test complex.

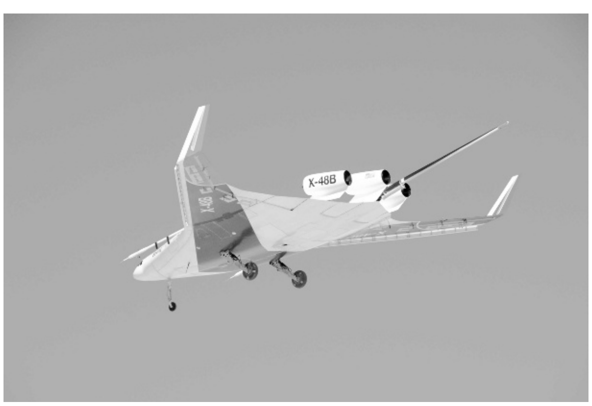

Figure 7. The X-48B on approach to its first landing.

represents the first attempt to obtain quality, scalable data from both wind-tunnel and flight test.

The Boeing Company has subcontracted to a British firm, Cranfield Aerospace (Cranfield, Bedford, United Kingdom), the design and fabrication of two high-fidelity 8.5% scale models of a notional prototype (full-scale) aircraft. Careful attention has been paid to the scalability of data in order to infer, as much as possible, the flight characteristics of the full-size aircraft from the subscale flight test. The design of the shape of this aircraft has been developed and refined over many years using both CFD analysis and limited wind-tunnel test data. Upon completion of the first of the two Cranfield Aerospace–built models, a wind-tunnel entry at NASA Langley's Full-Scale Wind Tunnel was performed in March of 2006. This vehicle matched identically the second, flight-worthy model, which would undergo subsequent flight test. An extremely high-quality wind-tunnel database for the X-48B was obtained in over five straight weeks of testing. This database, along with CFD supplements, was used to produce the flight control law derivations that would later be used to control and stabilize the aircraft in flight.

Once again, the years of careful and methodical design, using the best analytical and CFD tools, and calibrations with wind-tunnel data, have yielded another excellent-flying airplane. The X-48B BWB first flew on July 20, 2007, and has since (as of print date) had a total of five successful research flights. Because of the quality of the analysis tools, the pilot commented that the aircraft flies very much like the simulator, validating that the work of the design and flight test team was worthwhile and accurate. No surprises were encountered on the first or subsequent four flights, and the handling qualities of the aircraft as reported by the pilot during the various flight test maneuvers have been consistently excellent.

The X-48B aircraft will be flown into late 2007 and early 2008 and as many as 30 to 40 flights are possible. High-quality flight test data, characterizing fully the aerodynamic and stability and control derivatives of the configuration are the expected outcome. A great number of high-quality flight test documentation and technical papers are likely to result from this flight test effort. It is hoped that the products will be sufficient to significantly reduce the risk associated with taking the next step of designing and building a much larger, manned prototype aircraft. When this step occurs, the circle of CFD-to-flight will have been completed yet again.

Summary

This article describes and provides examples of successful CFD application to the design process of three true X-planes. The process of conceptual design, CAD modeling and refinement, followed by CFD methods application and further refinement is described. Specifically, how CFD can aid in the design of a wind-tunnel model to yield few, if any, surprises during wind-tunnel testing is explained. The process of using wind tunnel data to directly correlate to the CFD database has been described, in addition to calibrating the CFD methodology used. It was asserted that in some cases, the CFD database can prove useful in validating that the wind tunnel data reduction is being performed correctly.

CFD can be and has been an enabling technology on the path to getting a new aircraft shape to flight. Controlling an inherently unstable configuration is critically dependent on determination of its aerodynamics and stability derivatives; CFD can provide preliminary estimates of these quantities accurately enough for the development of early control laws and a flyable simulation. Configuration assessments and incremental redesign can then be accomplished in a deliberate fashion, with the goal of arriving at a final configuration to be committed to more detailed (and expensive) analysis leading toward a flight model, with greatly improved chances of success. ❑

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Endnotes

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Test and Evaluation of Tactical Missile System Using Electro-Optical Tracking System

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Test and Evaluation (T&E) play a significant role in the development of missile systems. Effective planning of the test procedures and efficient execution of the same, using high performance range instrumentation systems, considerably reduce the development cycle and make the product more reliable and efficient. Despite the number of simulation methodologies available in the world for testing the performance of weapon systems, live testing plays the most significant role in establishing the technology and providing user confidence. Precise agreement with a synthetic trajectory is one of the most critical parameters in the design and evaluation of a weapon system. In the domain of tactical missile defense, another significant derived parameter happens to be the miss distance (i.e., the minimum distance by which the missile misses the target). Accurate estimation of miss distance apart from measurement of multiple trajectories helps in analyzing the performance of various on-board systems. Accuracy also plays a vital role in evaluating the trajectory. In this context, an electro-optical tracking system plays a major role in performing real time autotracking of missiles and targets, as well as in computing the miss distance. With the advent of high resolution video technology and infrared imagery, along with development of high performance image processing algorithms, the task of evaluating a tactical weapon system becomes more interesting. This article explains the role of T&E *in the development of tactical missile systems. It further presents the electro-optical tracking system as a prime tool toward realization of this process and discusses various concepts of tracking, different error parameters of the system, and calibration methodologies to minimize errors and provide accurate data for the system under test.*

Key words: Accuracy; error budget; flight/field testing; synthetic trajectory; image processing; miss distance; simulation; target detection; trajectory; weapon system development.

Tactical ballistic missiles consist of three groups of subsystems: propulsion, guidance and control, and warhead. The main distinction between a ballistic missile and an unguided artillery rocket is the guidance and control system—the most expensive and technologically most advanced subsystem in a ballistic missile. Further, guided missiles are usually multistaged, enabling them to travel longer distances than an artillery rocket. The guidance and control of a missile consists of an inertial reference unit based on an array of gyros and accelerometers, a computer, a control mechanism to change the missile's flight path, and power packs for the electronics and controls. Normally, a long-range missile gets exposed to a wide range of natural as well as induced climatic and dynamic environments, including electromagnetic environmental effects (electromagnetic interference, electromagnetic compatibility, electromagnetic radiation, electrostatic discharge) and lightning effects. So, all the subsystems of the missile together with the seeker or sensor(s) should properly be tested and evaluated for reliability, performance, and safety before being placed in operation.

Role of T&E

T&E provides the means for determining to what extent the weapon system satisfies its requirements, how well it functions in the operational environment, and whether it should continue into production. T&E involvement begins at the time a new program is initiated and continues throughout the life cycle of the weapon system. During the conceptual phase, the involvement of T&E personnel is relatively small, consisting primarily of gaining familiarity with system requirements, technical approaches, and planning. The most important aspect of this early phase is sound T&E planning.

Once the missile system is introduced into service, T&E is performed in support of software and hardware configuration control, evaluation of product improvements and engineering change proposals, and evaluation of problem areas detected in the operational environment.

The various steps in T&E are:

- Analytical study: Review of technical documents, drawings, and schematics to the extent of complete understanding of the system. This identifies the strong and weak points.
- Laboratory/field test: This involves operation of various subsystems in a controlled open-loop laboratory environment to define performance parameters.
- Analytical simulation: This involves mathematical representation of the missile subsystems in closed-loop operation. Examples of most commonly used analytical simulations are trajectory simulation and lethality simulation. *Trajectory simulation* incorporates a nonlinear six degrees of freedom aerodynamic and kinematic model, provides detailed representation of guidance and autopilot functions, and a simplified representation of seeker and signal processing. *Lethality simulation* represents the terminal encounter to provide probability-of-kill information.
- Hardware-in-the-loop simulation: It is the closed-loop analytical-hardware representation of the missile system used to evaluate missile performance as affected by guidance, seeker, and signal processing. Sophistication and realism are obtained in this simulation by integrating as much of the missile hardware (and appropriate sensor environment) as possible. Hardware integration provides a valid, realistic, and complete representation of the missile operation that cannot be achieved during analytical simulation.

The goals of missile system T&E are achieved through the proper use of all the means of test and analysis at hand. All the previous tests provide required information to the designers regarding various performance parameters.

Flight testing

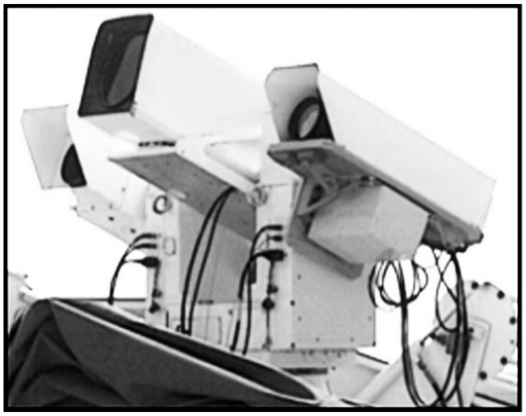
No simulation can ever replace an actual test flight. Test launch of a missile against a live target provides various mission critical data, which is otherwise not possible with individual tests. Further, it provides the real time integrated performance of the complete weapon systems under test. In the early days, emphasis was more on launching the missiles, and as a result, T&E data were derived almost solely from flight tests. Although considerably more data from other sources could have been used in the evaluation, it was not available because of inexperience in the missile system and T&E, as well as limited simulation technology and laboratory facilities. Over the years, missile systems have grown in sophistication and mission complexity. This forces a requirement for more simulation runs and a strong T&E center to evaluate the complex weapon system performance.

Background of test range

The most crucial aspects of testing a tactical missile system are the tracking of the missile, tracking of the target, and estimation of the miss distance of the missile from the target. The test event has to be evaluated in a test range from a system, which should not be a part of the weapon system. Further, the instrumentation system should preferably be vehicle independent to capture significant data even in case of an on-board failure. The miss distance should be computed from the same sensor measurement to minimize system errors. The system that best fits this requirement is the electro-optical tracking system (EOTS).

In a test range scenario, a number of such systems with multiple sensors are deployed to support such trials in addition to other trajectory measurement devices like radar, differential global positioning system, etc. EOTS plays a crucial role in such trials because of vehicle independent trajectory, very accurate measurement methods, and image processing methods to handle low altitude and high speed targets.

Application of electro-optical sensors in satellites and spacecrafts for detection and transmission of weather data, identification of Earth's resources, and determination of composition of atmosphere of other planets has had striking results. Remote sensing devices, consisting of electro-optical sensors operating in the infrared region are operational. During the past 30 years, the design of optical instruments has been dramatically improved by the use of computers. The variation of optical image quality as a function of field of view and spectral bands can be evaluated through computer programs. In the past, the telescope's field of view was very small because it was used for looking at celestial bodies. At present, however, the extensive application of sensors in aircraft, space, and missile programs requires wide angle field of view and high



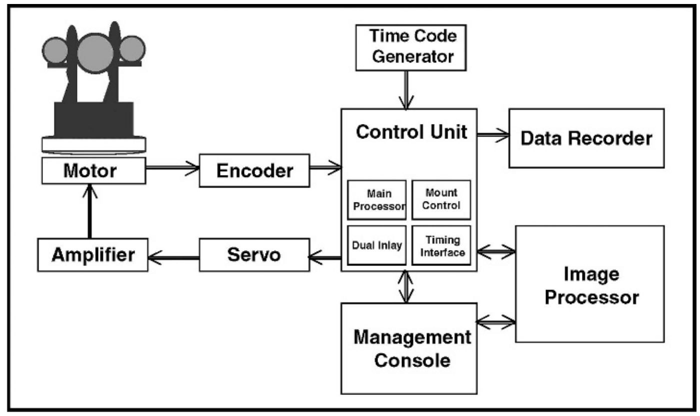


Figure 1. (Left) Electro-optical tracking system. Figure 2. (Right) Block diagram of electro-optical tracking system.

quality optics, which demands the development of large refractive elements. Large optical elements made of glass, silicon, and germanium have been tested and used as lenses. To maintain a high image quality in optics despite temperature variations, researchers have included corrective elements in the design. The positions of these elements are monitored by microprocessors. Larger fields of view have been achieved by incorporating complex scanning mechanisms into the design. The need for higher sensitivity forced a different approach to electro-optical sensor problems in the middle to late 1970s. Not only the detector but the preamplifier and other signal conditioning circuitry were housed in the focal plane. The implementation was eased by the invention of Charge Coupled Devices (CCDs) in the early 1970s. In particular, forward looking infrared imaging sensors, developed in the same period, incorporated a few hundred detectors as a linear array assembled using thin film technology.

Electro-optical tracking system

Electro-optical imaging and infrared systems have the advantage of being passive devices where no transmission of energy occurs. This fact denies the enemy detection and advance warning. The radiation of active microwave radars, on the other hand, can be detected by the enemy, providing a valuable tactical advantage. The passive nature of electro-optical imaging and infrared search and tracking systems, together with current emphasis on stealth technology (whereby radar detection is reduced because of the reduced radar cross-section of the targets), have greatly expanded the role of these systems. Because infrared systems are passive devices containing only a receiver system, they usually weigh considerably less than active microwave systems with both a transmitter and receiver.

An integrated electro-optical tracking range instrument is a multisensory-based automatic tracking system made to provide accurate measurement of the trajectory of the flight vehicle in space during its initial course. The system has the following objectives:

- Because of the concept of line-of-sight tracking and real-time image processing, the system provides precise trajectory information of the target right from takeoff till the imaging limit in the infrared band (3–5 μm/8–13 μm).
- The system provides trajectory information as required by the range safety officer for critical safety decision making in real time.
- Because of very high accuracy, the system is used as a reference system for the calibration and bias-estimation of other tracking instruments. This is useful during range validation.
- The system provides tracking video of the target along with the quick look data, which provides first-hand information about flight behavior immediately after the mission.

Because of automatic video tracking, the system provides useful information about different mission critical parameters during various trials, including multitarget trajectory and miss distance.

The basic system has two parts: the *multisensor mount* and the *control electronics*. The mount is equipped with a number of sensors:

- Monochrome CCD camera with 1800-mm optics,
- Infrared camera (3–5 μm) with dual optics,
- Color CCD camera with 1350-mm optics.

The monochrome CCD sensor is centrally mounted and serves as the prime sensor for system calibration and tracking in the visible range. The remaining two sensors are deployed on either side of the mount as shown in the *Figure 1*.

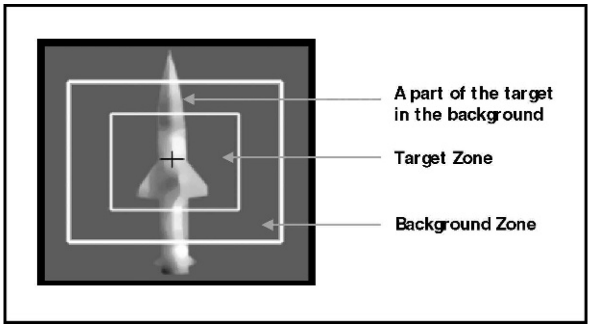


Figure 3. Centroid-based image processing.

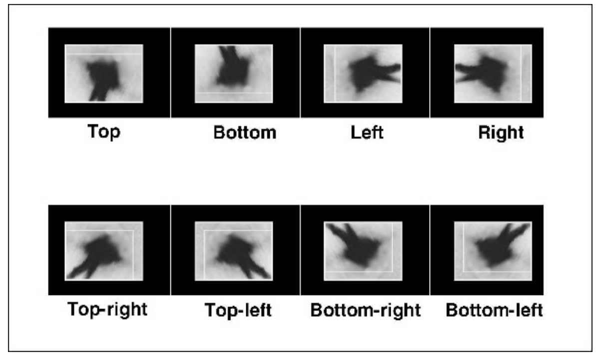


Figure 4. Edge-based image processing.

The mount has two degree of freedom. In azimuth, it can rotate continuously whereas in elevation, it can rotate from -10° to $+190^\circ$. Thus it can track a flying object from any direction. The mount is equipped with inductosyn (a resolver whose output phase is proportional to the shaft) to measure the angular position, which can further be transmitted to the control unit through the multimode fiber-optic cable. The entire processing is carried out in the control unit as shown in *Figure 2*.

A number of real time tasks are performed on the virtual machine environment (VME) system. A master processor controls the data handling, computation, and data transfer along with closed loop control. The system provides angular information about the central sensor axis, which is called the bore sight. Details of various errors involved in the system are given in a subsequent section. With a number of calibration algorithms, the system is able to minimize the errors and provides the most accurate positional information in terms of azimuth and elevation angles. It is worth mentioning here that the target angular data as measured by the system is accurate provided the flying object is always in the bore sight. This can only be possible when the system automatically tracks the object. This is challenging because there is no active link between the system and the flying object. Hence, the system tracks the object by the concept of real time image processing using the principle of automatic target detection and tracking. This is performed by a VME-based automatic video tracker, which serves as the nerve center of such systems.

Video tracker. The basic system has a front-end digitizer to grab the image in real time and to digitize the image. The operator defines an area in the digitized image for target detection. Then the processor generates the histogram and using basic image processing sequences detects the target. The tracking process can be centroid or edge type, based on contrast of the image, or it can be correlation type, based on the shape of the image.

Centroid algorithm. The centroid algorithm is used when the image has good contrast and uniform background. The frame grabber acquires a composite video signal from the camera, digitizes it, and stores it in the grabber memory. Depending on the tracking window selected by the operator, the following tasks are performed in real time:

- grabbing,
- median filtering,
- thresholding.

Edge tracking algorithm. When the system is required to auto track an elongated object, then the centroid algorithm fails because a part of the target falls in the background as shown in *Figure 3*.

Hence the auto tracker starts dragging to detect the centroid of the target. This leads to failure of the auto tracking. To avoid this problem, researchers have implemented an edge tracking algorithm. This method is similar to the centroid method of auto tracking except for the process of calculating the threshold. Here the threshold is calculated based on the edge selected (taking 2 line/pixel boundary at the edge selected) as shown in *Figure 4*. This algorithm performs best when tracking missiles with smoke and flame.

Correlation algorithm. A correlation algorithm is used when the target has many features and is embedded in a clutter background. In this method, tracking is accomplished by matching the location containing a stored reference image acquired in the first frame with a larger search image acquired in subsequent frames. The reference image is known as the *template* or *reference window*, and the bigger search image is known as the *search window*. The size of the search image vis-à-vis the reference image is decided by the maximum movement of the target expected from one image frame to the next frame. The search window size can vary between 5% and 50% of the field of view available.

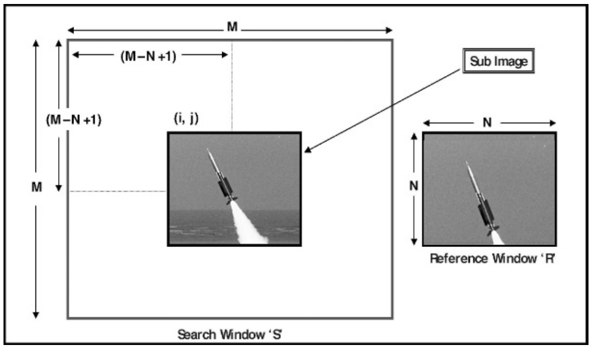


Figure 5. Correlation-based image processing.

The location of the template within the search window is computed by finding the mean compensated sum of absolute differences in gray levels between the template and the search image. The scheme is pictorially represented in *Figure 5*.

Predictive filters. During temporary target obscuration, this mode is triggered by an error invalid command issued by the video tracker system because of loss of target lock. This command will initiate the predictive mode and predicts the Δx, Δy angular errors using the past history of the gimbals' movement until the video tracker system recovers and locks on to the target in the specified time. To accomplish the tracking function during obscuration, a simple N-point filter predictor as given in the following list is generally used:

- a linear-N-point filter predictor,
- a quadratic-N-point polynomial filter predictor.

System Error Budget

Overview

The mount and tracking sensors are high-precision instruments; however, there is a need to estimate the overall error budget before computation of the trajectory.

Mechanical precision

Mechanical precision is the basic static accuracy of the mount. It is calculated by taking the root sum of the squares of the individual errors.

Instrument measurement accuracy

Instrument measurement accuracy (IMA) is the accuracy of the mount and track TV camera and optics under dynamic conditions. It defines the accuracy of the bore sight of the track optics. Systematic error correction is being applied in real time using the calibration coefficients to increase the accuracy of the system. The IMA is affected by the stability of the bore sight of the tracking TV camera under zoom conditions. To achieve the best accuracy, it is better to use a fixed focal length sensor. In the case of a zoom lens, the IMA will be larger. It may be possible to characterize the zoom bore sight wander to reduce this error.

Dynamic tracking accuracy

Dynamic tracking accuracy (DTA) is the accuracy to which the position of the target is known assuming the target is off bore sight. The automatic video tracker (AVT) measures the position of the target and its errors are included in the definition. The DTA accuracy depends on:

- The field of view of the track TV as the AVT measures in pixels.
- The size of the target. The AVT requires a number of pixels to achieve subpixel accuracy.
- The selected AVT algorithm.

For the centroid (contrast) algorithm, the center of intensity is calculated and not the center of the target. The dynamic measurement accuracy calculation assumes a uniform target such that the center of intensity and center of area are the same. For the correlation algorithm, the center of the target is defined by the operator. When auto-tracking starts, the position of the target in the tracking window is defined as the center of the target. In edge mode, the edge of the target is autotracked, and therefore the accuracy is relative to this edge and not to the center of the target. All the errors assume a uniform ambient temperature.

Definitions

The factors in *Table 1* contribute toward the overall error budget. A number of calibration methods like encoder origin, horizontality star calibration, target board calibration, infrared harmonization, color camera harmonization, etc., are performed before any trial for minimizing the overall error budget.

Multitarget Tracker

The multitarget tracker works on the VME bus with the video signal captured from the mount. The basic

Table 1. Sources of error

Miss level	Cross-hair stability
Nonorthogonality	Optical droop
Mount skew	Sensor skew
Mount droop	Encoder calibration error
Elevation shaft bending	Magnetic field
Encoder error	Refraction error
Wind up	Sensor dynamic error
Dynamic encoder error	Digitization noise
Residual parallax	Automatic video tracker jitter
Time uncertainty	Automatic video tracker accuracy

system is a full field of view video processor, which detects the signal based on its contrast. These signals are called "echoes." Then based on certain target characteristics, the system filters the undesirable signals and selects relevant signals called the "tracks." The system then matches these tracks to the user defined data sets to classify them. Based on the class definition, the system controls the mount movement.

The basic system has two parts. The front end processor is known as the processor board, and the backend processing is performed by VMPC6C. The 50-Hz analog video is captured in real time by the processor board. It digitizes the video into 768 × 288 × 8 bits format. Further it performs a series of treatments to the digitized video. In the first 20 ms, it performs the acquisition, digitization, and filtering of noise. In the next 12 ms, it performs contrast extraction and a few treatments. In this stage, it applies the dilation and reduction filter, performs thresholding, and transfers images to the VMPC6C. In the next 18 ms the inlay operation is performed on the video followed by echo detection, track detection, and classification. This is performed by a field programmable gate array (FPGA) with a 50,000 gate Altera. The system operates at a sampling frequency of 15 MHz. It detects about 20 objects and processes 5 tracks. The target offsets along with the mount angles are transmitted in real time to the central test computer. Special triangulation software runs in real time to compute the position of the missile and the target. Based on this trajectory data, the system computes the miss distance.

Conclusion

This article highlights the T&E of tactical missile systems using an electro-optical tracking system as the prime sensor. It explains the procedure of auto tracking to obtain the most precise trajectory. It also explains the procedure to capture both the missile and the target using the same sensor and the computation of miss distance. Because the miss distance is computed using a single sensor, it gives the most accurate value. In this article, we examine in detail the various components of errors in an optical system. The data so extracted from this system provide the necessary information to the designers for further refinement of the weapon system. ❑

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Reliability Growth of Mobile Gun System During Production Verification Test

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Product verification testing (PVT) plays an important role in the verification and demonstration of key performance parameters and system reliability of autonomous and manned systems. Considerable effort was put into improving reliability of the Stryker Mobile Gun System (MGS) before and during PVT. During PVT for the Stryker MGS, an unprecedented reliability growth rate of 0.38 was achieved. This article describes implementation of systems engineering principles employed during the MGS program, as well as system abort data analysis conducted using reliability growth analysis and the Design Actions Report and Tracking system. During reliability growth testing, it is very important to have a proper understanding of the test data that trigger proper engineering analysis and consequently fuel reliability growth of the system during its developmental testing. In order to substantially improve reliability of the system during product qualification testing or PVT, it is imperative to have well defined failure definition scoring criteria, established engineering root cause analysis processes, fast implementation of verified design fixes, and Design Actions Reports and Tracking that address observed failure modes. This article discusses the reliability methodology utilized during PVT of MGS as well as some of the systems engineering principles employed to actively improve the design of MGS. Such an approach completes the Test-Find-Fix-Test cycle, further improves MGS reliability, and meets the requirements for the mission equipment package. Substantial efforts were made not only to capture positive and negative outcomes of this program, but also to mature the MGS program into a design-for-reliability methodology that can be utilized in future programs with even greater success.

Key words: Product verification test; reliability; reliability growth analysis; Test-Find-Fix-Test cycle.

A recent report from the Defense Science Board Reliability Task Force suggests that almost 80 percent of military programs fail a reliability test the first time. Such findings indicate that reliability is usually not adequately addressed during the design process, and the program requires substantial redesign efforts before the product can be fielded. In December 2007, the Army Acquisition Executive, The Honorable Claude Bolton, published a memo[1] in which he proposed the implementation of the reliability test threshold values and reliability best practices that would help a program focus on reliability during all stages of development. The Honorable John Young, Under Secretary of Defense for Acquisition, Technology, and Logistics, has directed that

> "…*effective immediately, it is Department policy for programs to be formulated to execute a viable RAM strategy that includes a reliability growth program as an integral part of design and development. Additionally, RAM shall be integrated within the Systems Engineering process.…*"[2]

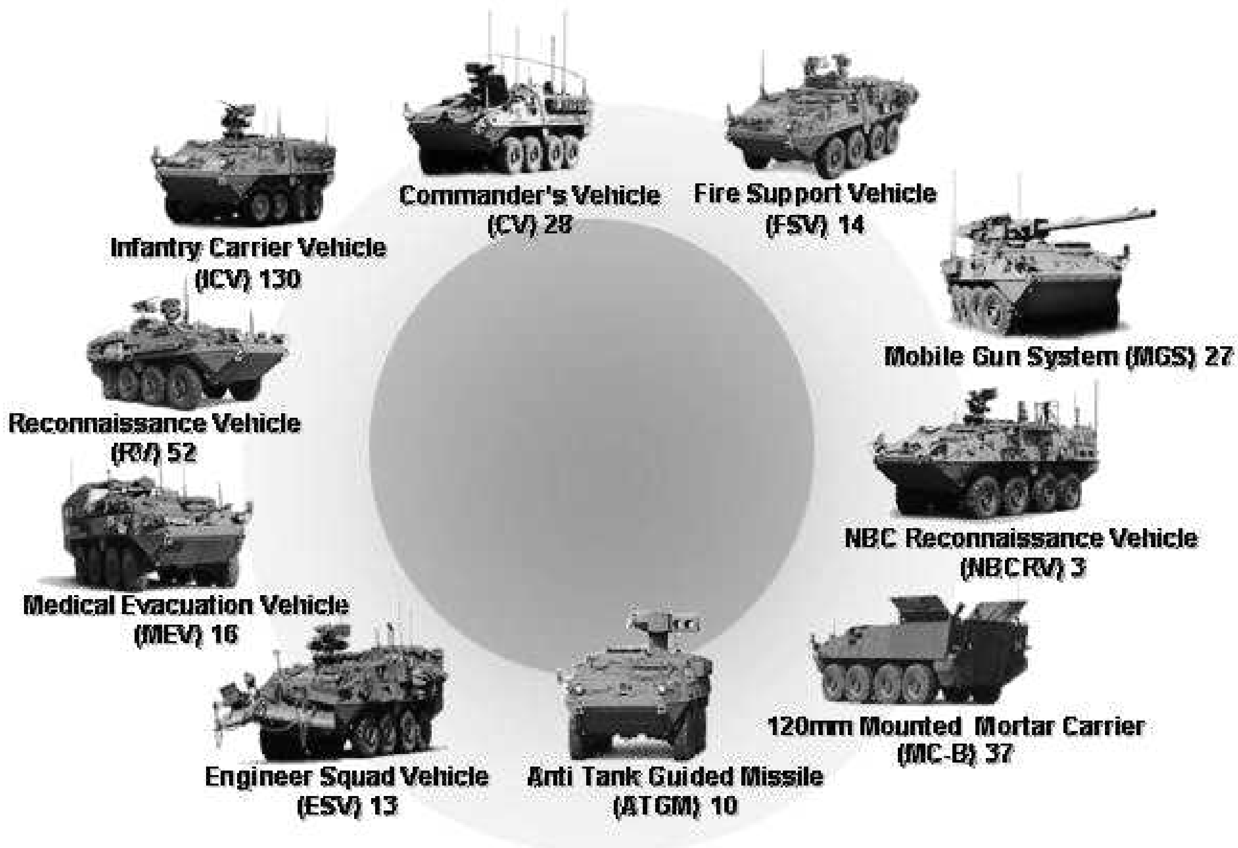

Figure 1. Stryker family of vehicles.

Major change in the U.S. Department of Defense reliability policy dictated by insufficient attention to reliability during product development will trigger some changes in program management as well as in the systems engineering organizations. That is why it is extremely important to capture positive lessons from successful programs such as the Stryker Mobile Gun System (MGS).

In this article, the authors discuss three major factors that ensured the MGS program met its reliability requirements during product verification testing (PVT):

- Program Management–Integrated Team,
- Systems Engineering–Reliability Attainment,
- Reliability Growth Analysis.

The main intent of this article is to illustrate practical applications of these factors and some near-term payoff programs should receive in terms of performance and reliability.

Stryker MGS

The Stryker family of vehicles is an eight-wheeled military combat vehicle being used by the Stryker Brigade Combat Teams and assembled into 10 different variants with a common chassis *(Figure 1)*. Eight main designs were developed by General Dynamics Land Systems (GDLS) as the prime contractor, successfully tested, and then fielded with the U.S. Army during 2003–2005.

The Stryker MGS is by far the most complex and heaviest design of all the variants within the Stryker family *(Figure 2)*. It incorporates the common Stryker chassis and low profile turret with 105-mm gun that is equipped with an ammunition handling system and auto-loader. The Product Qualification Test (PQT) conducted in 2003 revealed a variety of reliability and performance issues within the MGS design, especially with the ammunition handling system and the mission equipment package.

Between 2003 and 2006, program management made unprecedented efforts to redesign the MGS mission equipment package with an emphasis on its ammunition handling system. GDLS took the challenge and dramatically revitalized its systems engineering organization. Such efforts set the stage for an increase in reliability during the redesign stage and then use of the proper Test-Find-Fix-Test procedure during PVT. The first reliability growth plan devel-

Figure 2. Mobile gun system.

oped by a group of internal and external reliability experts established a planned reliability growth curve that connected an engineering process with measured reliability. Interestingly, predicted reliability for PVT was very close to the actual demonstrated reliability in 2008.

Success factors of MGS PVT

There are two main stages of product development in any program design or redesign activities and reliability growth testing. In order to achieve reliability requirements during design and subsequent test stages, the engineering community must employ robust engineering principles during the design stage and then manage failure modes during the test stage with a wide scope of timely issued corrective actions. Thus, the systems engineering team ensures initial reliability growth and then continues to develop improvements during the test phase. The program management team provides detailed schedule, proper budget, and resource management that supports the engineering team. And finally, the interpretation of the data from the test using reliability data analysis will direct the engineering efforts and will provide a proper assessment of the existing and/or potential reliability of the system. Below we will discuss all three elements in greater detail.

Program management

An initial assessment of Stryker MGS reliability during PQT revealed the shortcomings of the existing reliability growth program. The program management team developed the following plan to address the reliability issues:

- Phase I—Additional reliability testing to evaluate effectiveness of the corrective actions developed from PQT,
- Phase II—Systems engineering process improvement,
- Phase III—Redesign of major subsystems and integration.

These phases took place between 2003 and 2006 and then the program went into PVT in 2006. The main emphasis during these steps was made on systems engineering revitalization that will be discussed in the next section of this article. A Systems Engineering Reliability Growth Plan was developed to include both redesign activities and planned reliability growth testing.

It is important to point out that during the design or redesign stage of the reliability growth program *(Figure 3)* the engineering team focused on an inherent reliability or hardware/software reliability. The main efforts of the design process target the ability of the system design to perform its function reliably and robustly over a useful lifetime. On the other hand, the next phase of the Reliability Growth Plan will uncover problems affecting the operational reliability, i.e., inherent and induced failures. The latter can be described as operator/user errors, maintenance errors, accidents, etc. We will discuss those categories of failures later in this article. The same systems engineering process described here can address both aspects of operational reliability during both phases.

The program management team, working together between the Program Management Office Stryker Brigade Combat Teams and GDLS, were able to plan, budget, and execute the Reliability Growth Plan

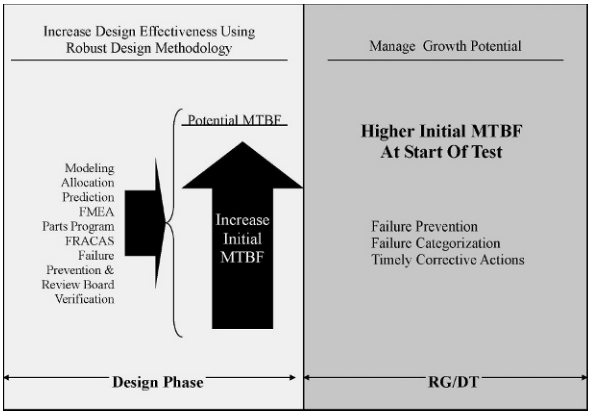

Figure 3. Reliability growth program.

successfully. Root cause analysis process followed by verification and validation of the corrective actions process became the major driving force behind the reliability growth of the MGS. Communication and explicit information about design deficiencies, verified fixes, and validation processes were key contributors to the overall success of the program.

Systems engineering (SE)

Engineering information about system performance during testing can be considered as feedback of the process that had designed such a system. It became obvious that current SE processes lacked focus on the reliability of the system. This conclusion triggered a systems engineering revitalization process that had system reliability as a main deliverable of the SE process. In addition to a very well defined SE master plan that served as guidance for the MGS redesign processes, the SE organization must have solid processes that govern every day activities, and SE management must have the associated metrics that adequately measure such processes. Thus, the SE organization focused on reliability processes, and appropriate management metrics formed the engineering core that was instrumental in achieving reliability requirements.

With the help of an external consultant, a revitalized SE process was developed and later used with great success on the MGS program. The process combines analysis and review of the system reliability requirements, system and subsystem design (redesign) for reliability, testing for reliability, and corrective actions tracking. A multifunctional and multilevel team of system and subsystem engineers formed a Failure Prevention and Review Board that became the driving force of the design improvement and was led by the Program Management Office. Such a process was developed and copyrighted by Dr. L. Crow and is presented in *Figure 4*.

The Design Actions Reporting and Tracking (DART) process discussed here manages the discovered failure modes as well as associated corrective actions through a redesign process driven by the Failure Prevention Review Board. Each DART created for an individual failure mode by an Incident Screening Team defines the seed of the database that can be used as a management measure of the process.

Thus, we have all elements of the successful process—the multifunctional engineering organization, a well defined process, and management metrics to adequately assess both the flow and aging of the process.

Also, it was found extremely useful to form affinity teams that address different common aspects of the design, such as a fasteners team, leak prevention team, integration team, etc. Because of the length limitations of this article, it is impossible to describe all the important steps, elements, and milestones of the GDLS SE process. However, a few extremely important elements must be noted.

The DART process generates a closed-loop failure mitigation system that not only drives the engineering correction process, but also helps to make statistical inferences from the test. Furthermore, the DART process or any other Failure Reporting and Corrective Action System connected to a Design Failure Mode and Effect Analysis or Failure Mode, Effect, and Criticality Analysis as a failure mode discovery mechanism can be the main driving force of the design for reliability approach. This methodology is being used by GDLS now on other programs.

It is imperative to note that major elements of the SE process initiated on the MGS program are described in the new "Reliability Program Standard for Systems Design, Development and Manufacturing."[3] It summarizes the four main objectives of the new standard:

- understand the requirements,
- design for reliability,
- produce reliable system,
- field and maintain the product.

The first three objectives correlate to the described above DART process.

Reliability data analysis

The last factor of a successful program is reliability data analysis. Indeed, the final reliability test is ultimately feedback on the previously described processes. Without proper inferences derived from the test and adequate data analysis, it is impossible to measure the reliability of the program. Limited sample size and test time can bias the outcome of the data

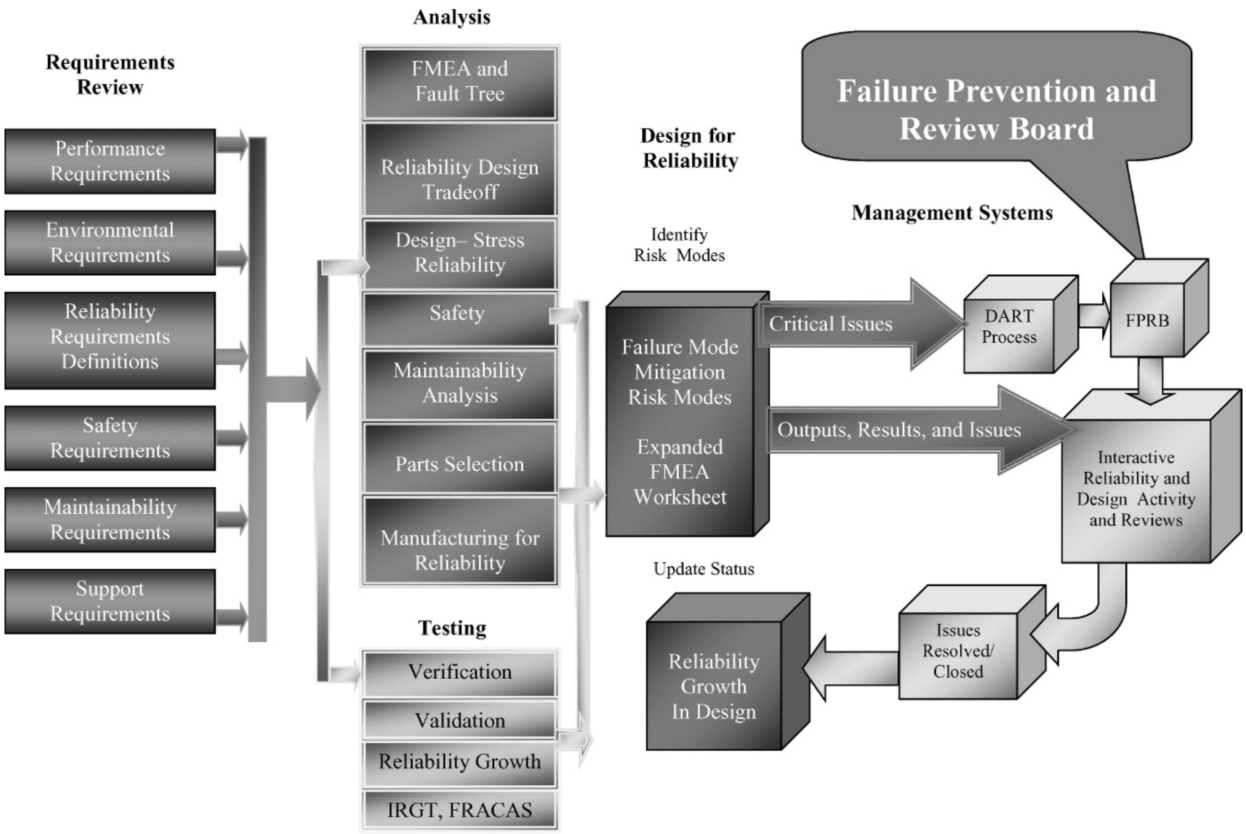

Figure 4. The design actions reporting and tracking process.

analysis and hinder the assessment of system reliability. But the reliability test is not only an evaluation tool but also a developmental tool, especially in the case of reliability growth. A developmental test or reliability growth test that is properly set up and planned can drastically improve the design of the system, even when it is conducted on a limited sample size.

MGS PVT was planned as a reliability growth test. The length of the test and planned idealized growth curve *(Figure 5)* suggested that the final measured reliability should be more than twice that of the initial measurement. The assumed reliability growth rate was 0.22, which is considered to be an average growth rate for Army developmental programs. It would be nearly impossible to perform reliability growth tests of a highly complex system such as the MGS without a highly efficient DART process and timely corrective actions incorporated on the test vehicles.

Reliability data analysis during the reliability growth test (i.e., reliability growth analysis) is described in details in MIL-HDBK-189[4] as well as in DoD Instruction 3235.1 Chapter 9.[5] MGS PVT reliability data analysis was described in depth in Chang and Rohall (2008). In this article we will emphasize a few important characteristics of the reliability growth analysis that helped to shape the assessment of MGS program, such as:

- failure definition scoring criteria,
- operational mission summary/mission profile,
- failure categories—inherent versus induced reliability,
- data grouping and modeling,
- instantaneous and cumulative mean rounds between system aborts.

Failure Definition and Scoring Criteria (FD/SC) and Operational Mode Summary and Mission Profile (OMS/MP) are the two most important contractual documents in the scope of work that govern the reliability performance of the system. The OMS/MP positively prescribes in what environment the system will be operated and what functions and in what sequence they should be performed. On the other hand, FD/SC discusses what is considered mission essential functions for the system, what constitutes as mission failure, measures of the severity level of such failures in regard to the mission success, and categorization of the chargeabilities of each failure. The matrix in the appendix to the FD/SC that addresses the potential failure modes as well as potential root causes is often translated from a System Design Failure Mode and an Effect Analysis and Fault Tree Model, the reliability tools that will help mitigate potential

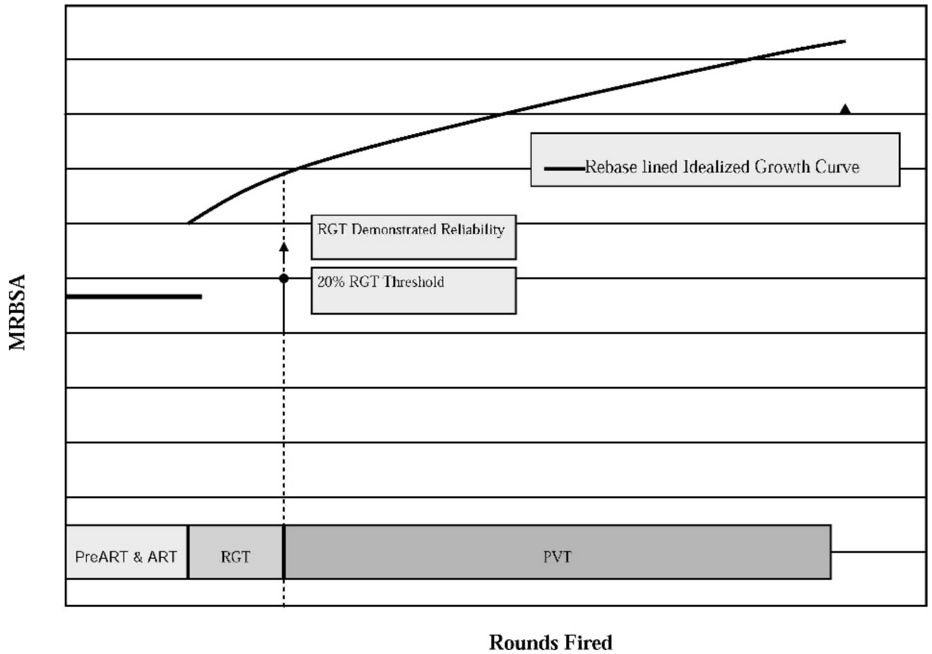

Figure 5. Mobile gun system idealized growth curve.

failure modes and attain reliability of the system earlier in the design stages. The matrix of FD/SC is a living document that needs to be updated as the configuration of the system changes due to engineering changes or redesign.

Properly executed tests per OMS/MP and a well written FD/SC will ensure a good reliability assessment during verification and developmental tests. Very often it requires performing a full root cause analysis on the failure incident before assessing its severity and thus properly employing FD/SC. It is extremely important that the reliability assessment and scoring process is completely decoupled from the prioritized list of design fixes.

Failure modes observed on the test have two distinct natures, i.e., inherent to the design (hardware failures) or induced by the operator and/or maintainer. From an inherent/induced perspective, one can distinguish hardware or design-related failures that characterize a system (hardware) capability to perform its intended functions. Such failures are usually called *hardware failures* and are associated with *inherent reliability*. That aspect of reliability is controlled by materiel developers and can be studied and addressed up front by employing the design-for-reliability discipline.

Inherent reliability or hardware failures can be further categorized as performance and reliability, signifying the difference in probability of repeat for each failure mode. For example, one can distinguish the performance failures as such failures when the system repeatedly fails under the given conditions of the test—wire melts at the specific current, bracket breaks at the specific load, etc. Alternatively, reliability failure is the failure that has a probability of occurrence of less than 100 percent. Such failures are usually associated with wear or aging. A particular reliability failure mode can be described by statistical distribution function with the specific independent life variable (hours, miles, rounds, cycles, etc.) The latter category of failures is historically the most used inherent reliability.

Induced failures, on the other hand, are associated with use, operating, or maintaining the system and usually are induced by the user. It is feasible to minimize the risk (probability) of such failure by making the design "bullet-proof" or less prone to such abuse, but it is usually associated with cost. Also, it is much harder to address such an event up front in the design process, and it is much less controlled by materiel developers. All such categories (user/operator/maintainer) can be generalized as induced failures.

Inherent and induced failures together form the operational reliability. The danger and caveat are in using operational reliability for the assessment of program reliability when materiel developers can control only inherent or hardware reliability during the design stage. Obviously, all failures including induced and inherent failures must be addressed during the reliability growth test or the developmental test. The preferred way to address both inherent and induced failures is with a design change that completely eliminates the failure mode. Hence, the program should have explicit requirements for hard-

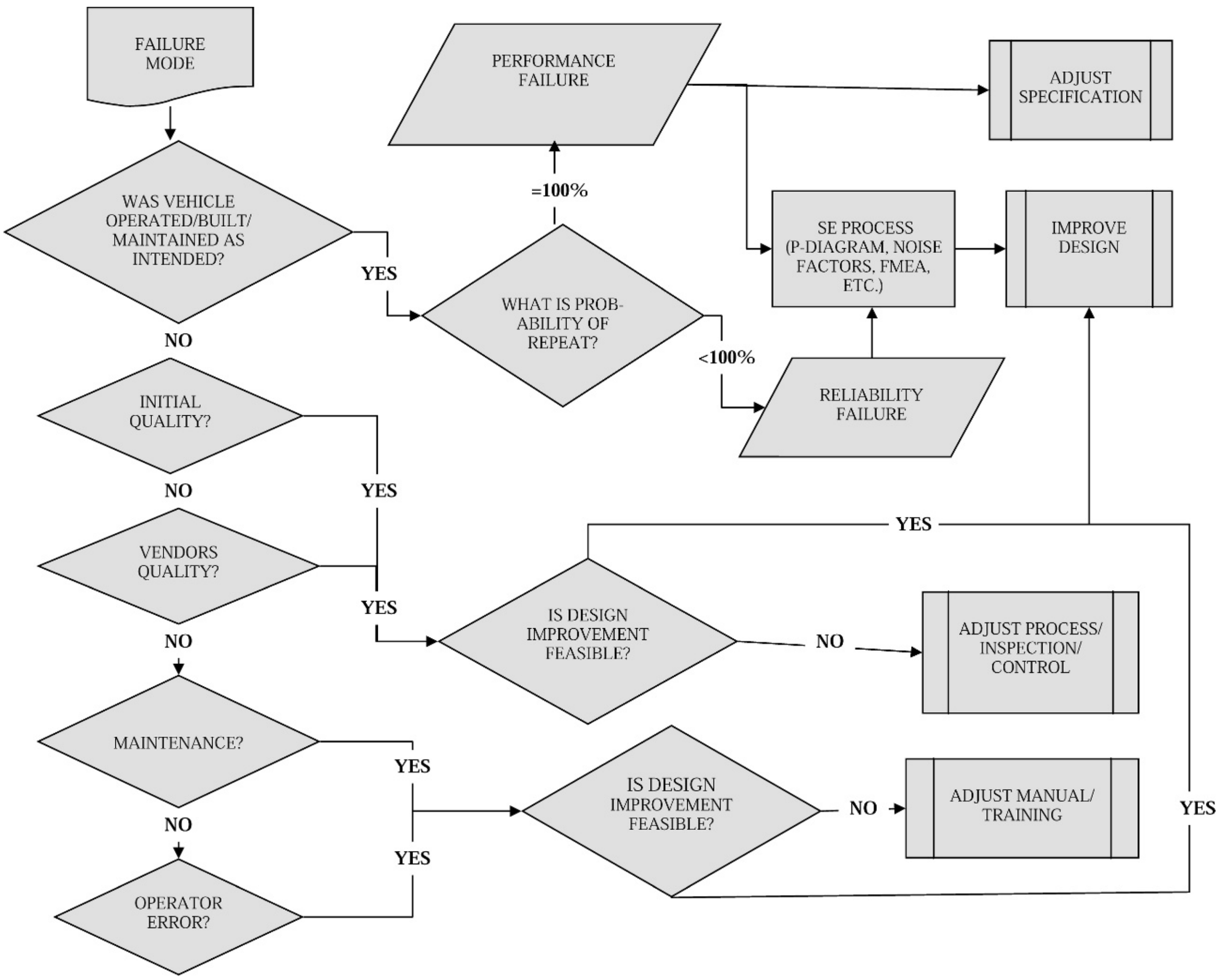

Figure 6. Failure categories.

ware or inherent reliability that indicate hardware capability to perform the mission and requirements for induced reliability as separate requirements.

In order to distinguish inherent and induced failures during the test, one can utilize the logic tree shown in *Figure 6*. The follow-up corrective action process can be derived from the failure category. It is understandable that induced failures do not depend on any independent life variables, such as miles, hours, etc., and cannot be modeled using statistical distribution functions.

Another important aspect of the reliability growth analysis, on top of sorting inherent and induced failures, is the proper way to prepare the data for reliability growth analysis modeling. It can become an issue when we consider complex systems on the complex test profile. MGS can be an excellent example of such systems.

As described in Chang and Rohall (2008), the MGS performs two major functions during OMS/MP—accumulate miles and firing rounds. The test profile prescribes 86 rounds to be fired for each 1,000 miles traveled. MGS PVT was conducted on three different vehicles in two different locations. The scheduled maintenance for different vehicles happened at different times. So the rates at which all vehicles were accumulating miles and rounds were different and varied by the vehicle, location, and time.

It seems to be feasible to use a grouped data approach because of the complexity of the test profile. There are two ways the data can be reduced—one is using known equivalent time (based on daily accumulation of rounds and miles) and then group it by the points that closely resemble the test profile of 86 rounds per 1,000 miles; another is using unknown equivalent time, forming individual groups of accumulated 86 rounds and 1,000 miles per vehicle and then combining them into an overall system. Both approaches have been tested and produced very close results as the test matured.

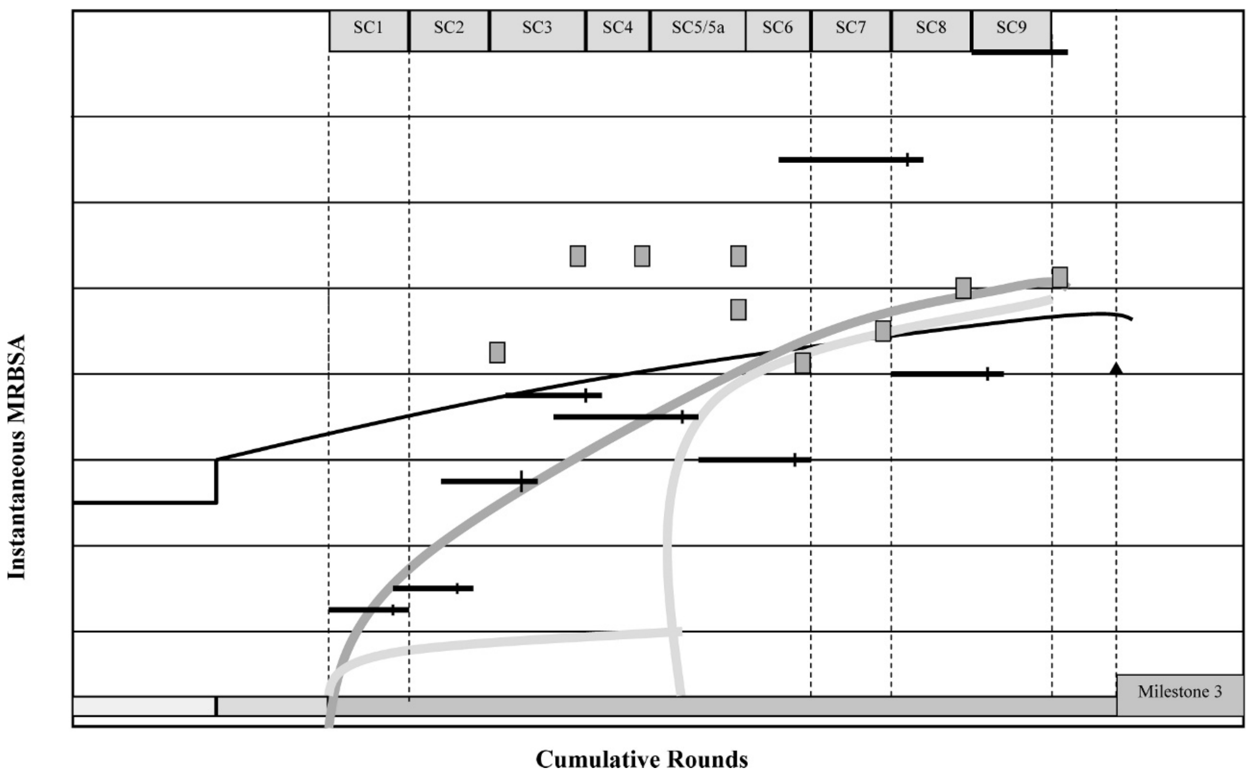

Figure 7. Planned and demonstrated reliability growth of mobile gun system during product verification testing.

The differences between such grouping techniques were obvious at the early stages of the test. Moreover, as the test progressed, the known equivalent time model became less stable and was more dependent on choosing pivotal points. Contrarily, the other model kept producing similar results throughout the conduct of the test. And, finally, it is natural to employ cumulative or average assessment of reliability during a verification or demonstration test when there is no major design alteration happening during the test. In such a scenario, the length of the test helps to build a confident estimate of the reliability of the system. One assumes no reliability growth sustained during the test.

In contrast to the above concept, any developmental or reliability growth test should employ the *instantaneous* concept for measuring and assessing reliability. Hence, reassessing the reliability as configuration of the system changes due to a corrective action implementation during the test must be properly measured using instantaneous values. Such factors can often be overlooked during initial stages of the reliability growth test when the impact of design changes is not as obvious as it becomes when the test matures.

Results and conclusions

The MGS PVT started in May 2006 and finished in April 2008. During the test, the MGS program displayed steady reliability growth, with the growth rate approaching 0.38 (alpha value), which is an extremely high growth rate compared to historical data of similar systems. In the allotted amount of time (miles and rounds), the program exceeded its objectives and confidently met the reliability requirements, as shown in *Figure 7*. It was an undeniable success of the program that its reliability since PQT improved by almost 10 times.

The authors firmly believe that all three factors described here helped to drastically improve the reliability of the MGS, namely:

- Program management as an integrated team that was a driving force behind the reliability growth program.
- Revitalized systems engineering within the materiel developer organization that was instrumental in executing the design-for-reliability approach as well as timely corrective actions during the test.
- Accurate and adequate measure of the program health during the PVT using reliability growth analysis. Proper understanding and analysis of the observed failure modes that led to the right tracking of the reliability growth provides positive feedback to engineering and program management.

In Chang and Rohall (2008), PMO Stryker Brigade Combat Teams expressed their observation of the MGS PVT as follows:

> *"The successful MEP system reliability growth program of MGS PVT can be attributed to the following factors:*

- The test program was planned to subject the system to test exposure and stress levels adequate to uncover inherent failure modes.
- *The program office considered the requirements of the test schedule and resources required to support the 'TAFT' procedure.*
- *The materiel developer conducted an effective systems engineering process to identify and implement effective corrective actions.*
- *The reliability team applied reliability growth analysis techniques and developed a methodology to track and assess the reliability growth at every test phase."*

A positive lesson from MGS PVT will be applied to many different programs by GDLS and perhaps other defense contractors. It is important to address reliability from the beginning of the program. Without attention to reliability and driving efforts by the program management office, it is impossible to expect the program to meet its reliability requirements. Also, designing for reliability that blends into the systems engineering process will make the reliability program a viable path to meet the reliability requirements. Reliability program plan execution will require a schedule and budget commitment, but the initial investment into reliability will be significantly less than the capital spent later to fix the design. ❑

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Endnotes

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The Radius of Curvature in the Prime Vertical

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The WGS84 Ellipsoid representation of the earth is an ellipsoid of rotation in which the polar axis serves as the axis of rotation. A frequently used equation in missile defense modeling and simulation is $N = \frac{a}{\sqrt{1-e^2\sin^2(\theta_G)}}$*, where N is the radius of curvature in the prime vertical at some point P on the earth's surface, a is the equatorial radius of the earth,* θ_G *is the geodetic latitude of P, and e is the eccentricity of the ellipse of rotation. This article provides a derivation of the equation.*

Key words: Earth; ellipsoid of rotation; modeling; radius of curvature; simulation; WGS84.

The World Geodetic System 1984 (WGS84) Ellipsoid representation of the earth (National Imagery and Mapping Agency, 1984) is an ellipsoid of rotation in which the z-axis (polar axis) serves as the axis of rotation. For any point P on the ellipsoid, the angle that the line L, the normal to the ellipsoid at P, makes with the equatorial plane of the ellipsoid is the geodetic latitude, θ_G, of the point. Let S_1 be the plane that contains the line L and the polar axis. Without loss of generality, since we are considering an ellipsoid of rotation, we may assume S_1 to be the x-z plane. Let E_1 be the intersection of the ellipsoid and S_1. (The intersection of any nontangent plane with the ellipsoid is an ellipse.) As depicted in Figure 1, the equatorial radius a is the semi-major axis of E_1, and the polar axis b is the semi-minor axis of E_1. Q is the point of intersection of L with the z-axis, and R is the other point where L intersects E_1.

Let S_2 be the plane that is perpendicular to S_1 whose intersection with S_1 is the line L, and let E_2 be the ellipse defined by the intersection of S_2 with the ellipsoid. In Figure 1 the darkened line segment, PR, represents the "edge-on view" of E_2. The *radius of curvature in the prime vertical* at P is defined to be the radius of curvature of the ellipse E_2 at the point P. In the literature, the magnitude of the radius of curvature in the prime vertical at P is stated to be

$$N = \frac{a}{\sqrt{1-e^2\sin^2(\theta_G)}}, \qquad (0)$$

where e is the eccentricity of E_1, defined to be

$$e = \sqrt{\frac{a^2-b^2}{a^2}}.$$

The Equations of the Ellipse and the Geodetic Latitude

The equation for an ellipse with semi-major axis of length a falling on the x-axis and semi-minor axis of length b falling on the z-axis is

$$\frac{x^2}{a^2} + \frac{z^2}{b^2} = 1. \qquad (1)$$

Solving for z (in the upper half-plane):

$$z = \frac{b}{a}\sqrt{a^2-x^2}, \qquad (2)$$

and differentiating twice:

$$z' = -\frac{b}{a}\frac{x}{\sqrt{a^2-x^2}} \qquad (3)$$

and

$$z'' = \frac{-ab}{(a^2-x^2)^{3/2}}. \qquad (4)$$

The eccentricity of the ellipse is defined to be

$$e = \frac{\sqrt{a^2-b^2}}{a}. \qquad (5)$$

In Figure 2, the angle between the line joining the origin and the point $P = (x_0, z_0)$ is the central latitude and is designated θ_C. Define the line segment T_1T_2 to be tangent to the ellipse at P. The line L that is perpendicular to T_1T_2 at P then meets the x-axis at angle θ_G, the geodetic latitude.

The tangent of θ_C is

$$\tan(\theta_C) = \frac{z_0}{x_0}. \qquad (6)$$

The slope of the tangent line T_1T_2 is the derivative, $z'(x_0)$. By perpendicularity, the slope of L is

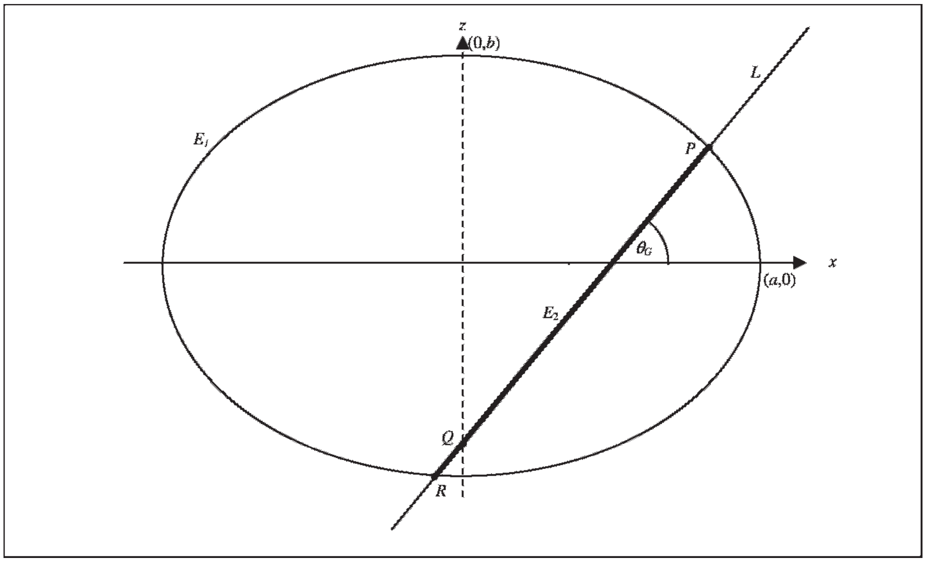

Figure 1. WGS-84 ellipsoid.

$$\tan(\theta_G) = -\frac{1}{z'(x_0)} = -\frac{1}{-\frac{b}{a}\frac{x}{\sqrt{a^2-x_0^2}}}$$
$$= \frac{a^2}{b^2}\frac{\left(\frac{b}{a}\right)\sqrt{a^2-x_0^2}}{x_0} = \frac{a^2}{b^2}\tan(\theta_C). \tag{7}$$

The Radius of Curvature of the Ellipse in the Plane

If, within a suitable region, z can be expressed as a twice-differentiable function of x, the formula for the radius of curvature within that region, as derived in Hille (1964), is:

$$N = \left|\frac{\left\{1+\left(\frac{dz}{dx}\right)^2\right\}^{\frac{3}{2}}}{\frac{d^2z}{dx^2}}\right| = \left|\frac{\left\{1+z'^2\right\}^{\frac{3}{2}}}{z''}\right|. \tag{8}$$

So for the ellipse, the Equations 3, 4, 5, and 8 yield

$$N = \left|\frac{\left\{1+\left(-\frac{b}{a}\frac{x}{\sqrt{a^2-x^2}}\right)^2\right\}^{\frac{3}{2}}}{\frac{-ab}{(a^2-x^2)^{\frac{3}{2}}}}\right|$$
$$= \frac{\left(a^2-e^2x^2\right)^{\frac{3}{2}}}{ab} = \frac{\left(a^2-e^2x^2\right)^{\frac{3}{2}}}{a^2\sqrt{1-e^2}}. \tag{9}$$

In particular, at the point (a, 0), the apoapsis, the

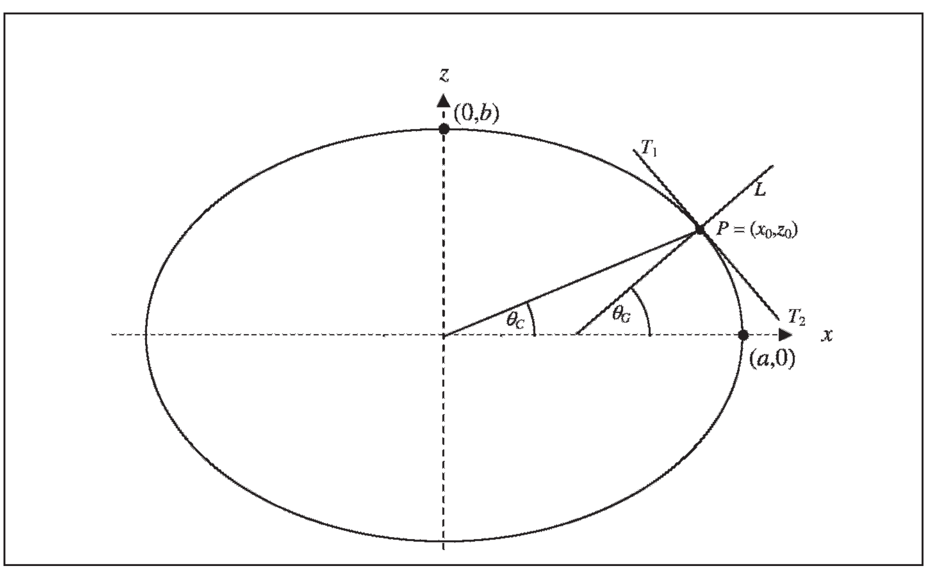

Figure 2. Central latitude.

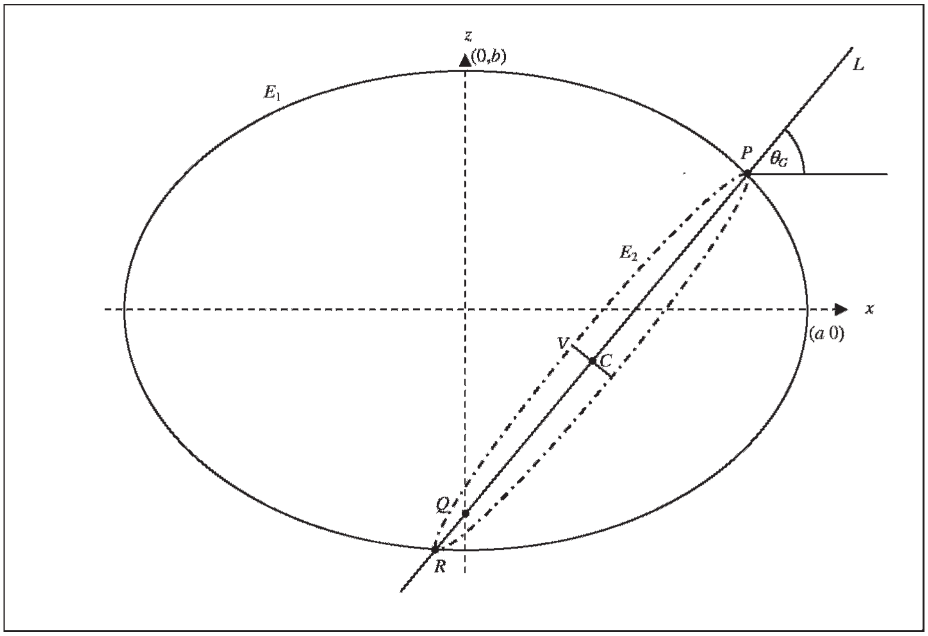

Figure 3. The nature of the ellipse E_2 made visible.

radius of curvature is

$$N = \frac{\left(a^2 - e^2 a^2\right)^{\frac{3}{2}}}{a^2\sqrt{1-e^2}} = \frac{a^3\left(1-e^2\right)^{\frac{3}{2}}}{a^2\left(1-e^2\right)^{\frac{1}{2}}}$$
$$= a\left(1-e^2\right) = a\left(1 - \frac{a^2-b^2}{a^2}\right) = \frac{b^2}{a}. \qquad (10)$$

By a similar argument, the radius of curvature at the point (0, b), the periapsis, is

$$N = \frac{a^2}{b}. \qquad (11)$$

In the case of either of the apsides, the radius of curvature is the square of the length of the opposite semi-axis divided by the length of the incident semi-axis.

The Radius of Curvature in the Prime Vertical

Figure 3 is meant to be a slightly perturbed rendition of Figure 1, wherein the nature of the ellipse E_2 is made visible. The point C bisects PR. By symmetry, it is seen that the line segment PC is the semi-axis of E_2 incident to P, and VC is the semi-axis of E_2 opposite to P. Therefore, based on Equations 10 and 11, the radius of curvature of E_2 at P is then

$$N = \frac{\overline{VC}^2}{\overline{PC}}, \qquad (12)$$

and by definition this is the radius of curvature in the prime vertical.

Let C have the coordinates (x_m, z_m) and set $\mu = \tan(\theta_G)$. Then the equation of the line L is

$$\mu = \frac{z - z_0}{x - x_0},$$

or

$$z = \mu(x - x_0) + z_0.$$

Squaring gives

$$z^2 = \mu^2 x^2 + 2\mu(z_0 - \mu x_0)x + (z_0 - \mu x_0)^2. \qquad (13)$$

From Equation 1 for the ellipse E_1 we have

$$\frac{x^2}{a^2} + \frac{z^2}{b^2} = 1$$

or

$$z^2 = b^2 - \frac{b^2}{a^2}x^2. \qquad (14)$$

Combining Equations 13 and 14 yields

$$\left(\mu^2 + \frac{b^2}{a^2}\right)x^2 + 2\mu(z_0 - \mu x_0)x + (z_0 - \mu x_0)^2 - b^2 = 0. \quad (15)$$

The roots of this quadratic equation in x are the x coordinates of the points P and R where L intersects E_1 (one of them is of course x_0). Dividing the sum of the two x coordinates by 2 gives the x coordinate of C, the midpoint. The sum of the roots of a quadratic equation of the form $\alpha x^2 + \beta x + \gamma = 0$ is $-(\beta/\alpha)$. Therefore, the x coordinate of C is

$$x_m = \left(\frac{1}{2}\right)\frac{2\mu(z_0 - \mu x_0)}{\mu^2 + \frac{b^2}{a^2}} = \frac{\mu^2 x_0 - \mu z_0}{\mu^2 + \frac{b^2}{a^2}}. \qquad (16)$$

From Equations 6 and 7, we have

$$x_m = \frac{\frac{a^4}{b^4}\frac{z_0^2}{x_0^2}x_0 - \frac{a^2}{b^2}\frac{z_0}{x_0}z_0}{\frac{a^4}{b^4}\frac{z_0^2}{x_0^2} + \frac{a^2}{b^2}} = \frac{a^4\left(a^2-b^2\right)}{a^6z_0^2+b^6x_0^2}x_0z_0^2. \quad (17)$$

By symmetry, all that is required to solve for the z coordinate of C is interchanging as with bs and x_0s with z_0s to obtain

$$z_m = \frac{b^4\left(b^2-a^2\right)}{a^6z_0^2+b^6x_0^2}z_0x_0^2 = -\frac{b^4\left(a^2-b^2\right)}{a^6z_0^2+b^6x_0^2}x_0^2z_0. \quad (18)$$

Let q be the distance between P and C. Then

$$q^2 = (x_0-x_m)^2 + (z_0-z_m)^2$$

that with equations 17 and 18 yields

$$\begin{aligned}
q^2 &= {x_0}^2\left[1-\frac{a^4\left(a^2-b^2\right)z_0^2}{a^6z_0^2+b^6x_0^2}\right]^2 + {z_0}^2\left[1+\frac{b^4\left(a^2-b^2\right)x_0^2}{a^6z_0^2+b^6x_0^2}\right]^2\\
&= {x_0}^2\left[\frac{b^6x_0^2+a^4b^2z_0^2}{a^6z_0^2+b^6x_0^2}\right]^2 + {z_0}^2\left[\frac{a^6z_0^2+a^2b^4x_0^2}{a^6z_0^2+b^6x_0^2}\right]^2\\
&= b^4{x_0}^2\left[\frac{b^4x_0^2+a^4z_0^2}{a^6z_0^2+b^6x_0^2}\right]^2 + a^4{z_0}^2\left[\frac{a^4z_0^2+b^4x_0^2}{a^6z_0^2+b^6x_0^2}\right]^2\\
&= \frac{\left(b^4x_0^2+a^4z_0^2\right)^3}{\left(a^6z_0^2+b^6x_0^2\right)^2},
\end{aligned}$$

and

$$q = \frac{\left(b^4x_0^2+a^4z_0^2\right)^{\frac{3}{2}}}{a^6z_0^2+b^6x_0^2}. \quad (19)$$

The other axis of the ellipse E_2 is the line segment passing through C, perpendicular to the x-z plane, and having endpoints on the ellipsoid. The equation defining the ellipsoid is

$$\frac{x^2}{a^2}+\frac{y^2}{a^2}+\frac{z^2}{b^2}=1. \quad (20)$$

The coordinates of the endpoints of the axis are therefore (x_m, y_m, z_m) and $(x_m, -y_m, z_m)$, where

$$\begin{aligned}
y_m^2 &= a^2\left(1-\frac{x_m^2}{a^2}-\frac{z_m^2}{b^2}\right)\\
&= a^2\left[1-\frac{\left(\frac{a^4\left(a^2-b^2\right)x_0z_0^2}{a^6z_0^2+b^6x_0^2}\right)^2}{a^2}-\frac{\left(\frac{b^4\left(a^2-b^2\right)x_0^2z_0}{a^6z_0^2+b^6x_0^2}\right)^2}{b^2}\right]\\
&= a^2\left[1-\frac{a^6\left(a^2-b^2\right)^2x_0^2z_0^4}{\left(a^6z_0^2+b^6x_0^2\right)^2}-\frac{b^6\left(a^2-b^2\right)^2x_0^4z_0^2}{\left(a^6z_0^2+b^6x_0^2\right)^2}\right]\\
&= a^2\left[1-\frac{\left(a^2-b^2\right)^2x_0^2z_0^2}{\left(a^6z_0^2+b^6x_0^2\right)^2}\left(a^6z_0^2+b^6x_0^2\right)\right].
\end{aligned}$$

So

$${y_m}^2 = a^2\left[1-\frac{\left(a^2-b^2\right)^2x_0^2z_0^2}{\left(a^6z_0^2+b^6x_0^2\right)}\right]. \quad (21)$$

Combining Equations 12, 19, and 21, we have

$$N = \frac{\overline{VC}^2}{\overline{PC}} = \frac{y_m^2}{q} = \frac{a^2\left[1-\frac{\left(a^2-b^2\right)^2x_0^2z_0^2}{\left(a^6z_0^2+b^6x_0^2\right)}\right]}{\frac{\left(b^4x_0^2+a^4z_0^2\right)^{\frac{3}{2}}}{a^6z_0^2+b^6x_0^2}} \quad (22)$$

The next step in this derivation is arcane, circuitous, and ugly, which, if there is no better way, probably accounts for its absence in the published literature. The author would very much appreciate seeing a more elegant presentation. The following makes frequent use of Equation 1 applied to point P:

$$\frac{x_0^2}{a^2}+\frac{z_0^2}{b^2}=1$$

or

$$a^2z_0^2 = a^2b^2 - b^2x_0^2.$$

That said, starting with Equation 22,

$$\begin{aligned}
N &= \frac{a^2\left[1-\frac{\left(a^2-b^2\right)^2x_0^2z_0^2}{\left(a^6z_0^2+b^6x_0^2\right)}\right]}{\frac{\left(b^4x_0^2+a^4z_0^2\right)^{\frac{3}{2}}}{a^6z_0^2+b^6x_0^2}}\\
&= \frac{a^2\left[a^6z_0^2+b^6x_0^2-\left(a^2-b^2\right)^2x_0^2z_0^2\right]}{\left(b^4x_0^2+a^4z_0^2\right)^{\frac{3}{2}}}\\
&= \frac{a^6\left(a^2z_0^2\right)+a^2b^6x_0^2-\left(a^2-b^2\right)^2x_0^2\left(a^2z_0^2\right)}{\left(b^4x_0^2+a^4z_0^2\right)^{\frac{3}{2}}}\\
&= \frac{a^6\left(a^2b^2-b^2x_0^2\right)+a^2b^6x_0^2-\left(a^2-b^2\right)^2x_0^2\left(a^2b^2-b^2x_0^2\right)}{\left(b^4x_0^2+a^4z_0^2\right)^{\frac{3}{2}}}\\
&= \frac{b^2\left[a^8-a^6x_0^2+a^2b^4x_0^2-\left(a^2-b^2\right)^2a^2x_0^2+\left(a^2-b^2\right)^2x_0^4\right]}{\left(b^4x_0^2+a^4z_0^2\right)^{\frac{3}{2}}}\\
&= \frac{b^2\left[a^8-2a^4\left(a^2-b^2\right)x_0^2+\left(a^2-b^2\right)^2x_0^4\right]}{\left(b^4x_0^2+a^4z_0^2\right)^{\frac{3}{2}}}\\
&= \frac{b^2\left[a^4-\left(a^2-b^2\right)x_0^2\right]^2}{\left(b^4x_0^2+a^4z_0^2\right)^{\frac{3}{2}}}\\
&= \frac{b^2\left[a^4-a^2x_0^2+\left(b^2x_0^2\right)\right]^2}{\left(b^4x_0^2+a^4z_0^2\right)^{\frac{3}{2}}}
\end{aligned}$$

$$
\begin{aligned}
&= \frac{b^2\left[a^4 - a^2x_0^2 + a^2b^2 - a^2z_0^2\right]^2}{\left(a^4z_0^2 + b^4x_0^2\right)^{\frac{3}{2}}} \\
&= \frac{a^4b^2\left[\left(a^2+b^2\right)(1) - x_0^2 - z_0^2\right]^2}{\left(a^4z_0^2 + b^4x_0^2\right)^{\frac{3}{2}}} \\
&= \frac{a^4b^2\left[\left(a^2+b^2\right)\left(\frac{x_0^2}{a^2} + \frac{z_0^2}{b^2}\right) - x_0^2 - z_0^2\right]^2}{\left(a^4z_0^2 + b^4x_0^2\right)^{\frac{3}{2}}} \\
&= \frac{\frac{a^4b^2}{a^4b^4}\left(a^4z_0^2 + b^4x_0^2\right)^2}{\left(a^4z_0^2 + b^4x_0^2\right)^{\frac{3}{2}}} \\
&= \frac{\left(a^4z_0^2 + b^4x_0^2\right)^{\frac{1}{2}}}{b^2} \\
&= \frac{a}{\left[\frac{b^2\left(a^2b^2\right)}{a^4z_0^2 + b^4x_0^2}\right]^{\frac{1}{2}}} \\
&= \frac{a}{\left[\frac{b^2\left(b^2x_0^2 + a^2z_0^2\right)}{a^4z_0^2 + b^4x_0^2}\right]^{\frac{1}{2}}} \\
&= \frac{a}{\left[\frac{a^4z_0^2 + b^4x_0^2 - a^4z_0^2 + a^2b^2z_0^2}{a^4z_0^2 + b^4x_0^2}\right]^{\frac{1}{2}}} \\
&= \frac{a}{\left[1 - \left(\frac{a^2-b^2}{a^2}\right)\left(\frac{a^4z_0^2}{a^4z_0^2 + b^4x_0^2}\right)\right]^{\frac{1}{2}}}.
\end{aligned}
\qquad (23)
$$

Since

$$\tan(\theta_G) = \frac{a^2}{b^2}\tan(\theta_C) = \frac{a^2}{b^2}\frac{z_0}{x_0},$$

$$\sin^2(\theta_G) = \frac{a^4z_0^2}{a^4z_0^2 + b^4x_0^2}.$$

Also, from Equation 5,

$$e^2 = \frac{a^2 - b^2}{a^2},$$

so that Equation 23 may be written

$$N = \frac{a}{\sqrt{1 - e^2\sin^2(\theta_G)}}. \qquad (24)$$

Graphical Representation of the Radius of Curvature in the Prime Vertical

To demonstrate the second assertion, referring to Figure 3, it is seen that the distance d between the point $P = (x_0, y_0)$ and $Q = (0, y_0)$ is

$$d = \sec(\theta_G)x_0. \qquad (25)$$

From Equation 24 and using Equations 1, 5, and 7, we have

$$
\begin{aligned}
N^2 &= \frac{a^2}{1 - e^2\sin^2(\theta_G)} \\
&= \frac{a^2\sec^2(\theta_G)}{\sec^2(\theta_G) - e^2\tan^2(\theta_G)} \\
&= \frac{a^2\sec^2(\theta_G)}{1 - \tan^2(\theta_G) - e^2\tan^2(\theta_G)} \\
&= \frac{a^2\sec^2(\theta_G)}{1 - (1 - e^2)\tan^2(\theta_G)} \\
&= \frac{a^2\sec^2(\theta_G)}{1 - \left(\frac{b^2}{a^2}\right)\frac{a^4}{b^4}\frac{y_0^2}{x_0^2}} \\
&= \frac{a^2b^2\sec^2(\theta_G)x_0^2}{b^2x_0^2 - a^2y_0^2} \\
&= \frac{a^2b^2\sec^2(\theta_G)x_0^2}{a^2b^2} \\
&= \sec^2(\theta_G)x_0^2 = d^2.
\end{aligned}
$$

Therefore

$$N = d.$$

❑

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