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**Developing Software Requirements Supporting Open
Architecture Performance Goals in Critical DoD System-of-
Systems**

15 September 2006

by

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Naval Postgraduate School**

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Abstract

To implement the capabilities conceptualized in the *National Military Strategy*, complex, secure networks of weapon systems, intelligence platforms, and command-and-control mechanisms must be seamlessly integrated and maintained over time. Accurate and timely information will enable *National Military Strategy* key tenets to be realized. These networks are central warfighting platforms in the information age.

As these capabilities are developed over time in an evolutionary manner, interoperability on the Net-Centric Warfare (NCW) networks is essential, and both hardware and software systems must be designed in an Open-systems Architecture (OA) fashion to accommodate the vast number of changes anticipated. Professional Program Management will be needed to successfully develop these key warfighting platforms.

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Keywords: Net-Centric Warfare, Interoperability, Open Systems Architecture, Software Requirements, System-of-Systems, Family of Systems

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Introduction

The National Military Strategy is the Chairman of the Joint Chiefs of Staff's guiding document for development of the future force and warfighting capabilities. It states:

Agility, decisiveness, and integration support simultaneous operations, the application of overmatching power and the fusion of US military power with other instruments of power. These principles stress speed, allowing US commanders to exploit an enemy's vulnerabilities, rapidly seize the initiative and achieve endstates. They support the concept of surging capabilities from widely dispersed locations to mass effects against an adversary's centers of gravity to achieve objectives.¹

The key word is "integration," as it prescribes interoperability requirements to a level never before achieved. Flexible networks of complex system-of-systems must be successfully developed to realize this strategic goal.

To implement the concepts presented in *National Military Strategy*, the Director of Force Transformation anticipates a new era:

As the world enters a new millennium, our military simultaneously enters a new era in warfare—an era in which warfare is affected by a changing strategic environment and rapid technological change. The United States and our multinational partners are experiencing a transition from the Industrial Age to the Information Age. Simultaneously, we are fully engaged in a global war on terrorism set in a new period of globalization. These changes, as well as the experiences gained during recent and ongoing military operations, have

¹Chairman of the Joint Chiefs of Staff. *National Military Strategy of the United States of America* (2004), 7.

resulted in the current drive to transform the force with network-centric warfare (NCW) as the centerpiece of this effort.²

This quote from *The Implementation of Network-centric Warfare* clearly indicates the direction that the DoD is taking in developing the next generation's warfighting capabilities. The success of the initial NCW systems deployed since Desert Storm, as limited as they were, revealed the potential battlespace domination offered through networked systems providing situational and informational superiority. One major challenge in constructing effective NCW systems is designing the network to seamlessly integrate existing, planned and future platforms and systems into a secure, fully interoperable, near real-time information system. The network will need to accommodate complex systems that may or may not have been designed to interoperate. The networked systems themselves are extremely complex and will have been developed decades apart. The network design must be open, flexible and able to adapt to this wide disparity of system-of-systems.

It is well understood that an Open-systems Architecture (OA) design is required to meet both current and future warfighting needs and is a critical element in net-centric warfare systems-of-systems concepts. These highly integrated systems are increasingly dependent on software solutions for integration into the net-centric scheme; therefore, software interfaces are one of the main keys for achieving the tactical and strategic synergies of the net-centric system. This research will focus on the challenges presented when the Department of Defense (DoD) conducts capabilities analysis and derives performance specifications for a software-intensive, net-centric, system-of-systems architecture that meets OA needs throughout the life of the system.

² Director, Force Transformation, Office of the Secretary of Defense, *The Implementation of Network-centric Warfare* (Washington, DC: author, 5 January 2005), 3.

Acquisition Essentials

You got to be careful if you don't know where you're going, because you might not get there! – Yogi Berra

There are several essential steps to successfully develop software-intensive systems or any complex system:

- Warfighter Functional Area Analysis/Functional Need Development
- Requirements Analysis and Development
- Communication with Potential Contractors via the RFP
- Source Selection of the Most Qualified Developer
- Intensive Management of the Development Effort
- Testing to Ensure Technical and Warfighter Requirements are Met
- New System Deployment and Training
- Effective Post-Deployment Support

Obviously, each of these steps has myriad activities and events that must be conducted to ensure that all facets are adequately addressed. Each step is dependent on how well its predecessor was conducted, recognizing that there is significant overlap between them. This overlapping period is critical to the process as the proponent of the preceding step must ensure that there is an excellent understanding of critical information needed at the next step and throughout the remaining system development and operational support. The impact of incomplete or ill-defined requirements on the following acquisition steps can be devastating, as planning, scheduling, budgeting, and resource allocation will be based on deficient information.

This research focuses on *Requirements Analysis and Development* and discusses both the input from the *Warfighter Need Development* step as well as the output with regard to the next step: *Communication with Potential Contractors via the RFP*. To develop the warfighting capability needed, it is obvious that requirements must be known; but exactly when and how the software developer learns of the total system requirements impacts cost and schedule proposals, as well as overall management of the developmental effort.

The Joint Capabilities Integration and Development System (JCIDS) is the guiding concept for developing warfighters' capabilities-based requirements. Warfighter requirements are communicated in terms of capabilities needed and include supportability capabilities, where appropriate. A series of capabilities documents—including Joint Capabilities Document (JCD), Initial Capabilities Document (ICD), Capabilities Design Document (CDD), and Capabilities Production Document (CPD)—are provided at the program initiation and throughout the system development phase to help ensure warfighting capabilities are well understood and the system under development satisfies the needed capabilities. These capabilities documents are developed within the framework of environments and constraints described in the acronym DOTMLPF—Doctrine, Organization, Training, Materiel, Leadership and education, Personnel, and Facilities.

Because the warfighter requirements are stated in capabilities-based language, a significant amount of systems engineering analysis is required to transform those user requirements into performance specifications that the potential contractors can understand. The individuals that draft these capabilities documents are typically operationally oriented, and the language used reflects that orientation. The Materiel Developer must interpret these requirements, providing much more detail with derived and implied system performance requirements.

The DoD Performance Specification development process transforms the warfighter requirements into terms that are more understandable for the system developer, usually the prime contractor. Typically, the system performance

requirements are decomposed through at least three levels using the Work Breakdown Structure (WBS) and the Systems Engineering Process (SEP) methodology. The concept is to provide the contractor sufficient detail with regard to performance, constraints, and intended environments without stifling innovative solutions to meeting those requirements. The number of WBS levels developed by the DoD is dependent on the complexity of the system and the engineering domain maturity. For example, the automotive engineering discipline is very mature, and a Level three WBS for a tactical truck system would most probably be sufficient. To determine whether the WBS and resulting performance specification are sufficient for the RFP, the Materiel Developer must ensure the contractor has sufficient information to develop the system needed by the warfighter. While easily stated, this presents a daunting challenge in complex systems, especially those that are software-intensive. Hardware-oriented engineering environments tend to be very mature, allowing developers to apply widely accepted standards for implied requirements such as maintainability and the ability to accept future upgrades or modifications. In contrast, software engineering relies almost exclusively on explicit requirements to attain the performance and quality attributes needed.

Software engineering is not mature, and there are few industry-wide standards for languages, tools, architectures, reuse, or procedures. Software developed for complex weapon systems is typically started from scratch with each new system; very little existing software code is reused. In addition, new languages and associated tools are introduced every few years. For this and other reasons, software programs grow exponentially in size and complexity, expanding desired capabilities but limiting the maturation process. The DoD Materiel Developer must recognize the relative immaturity of software engineering when developing the WBS and performance specification for software-intensive systems and, more importantly, compensate for that immaturity.

The current state of software engineering maturity drastically impacts an area of extreme DoD concern—Supportability. Hardware-centric performance specifications rely heavily on mature engineering environments to account for a

significant portion of the system's supportability performance. Using the automotive engineering example, there is little need of specifying supportability requirements such as features for oil, filter, tire and coolant replacement as they are industry-standard features that would be included in any competent design. There are few corresponding software engineering standards for supportability features, and most commercially based software is not designed for long-term use as is typically the requirement for DoD systems. There are literally hundreds of ways to build the architecture and construct the code for even the most basic software function. Without physical or established engineering techniques, the software developer is bounded only by his or her imagination and creativity in satisfying broad specifications. The resulting software may function correctly, but may not possess the OA design needed to effectively maintain, upgrade, or interface it with the constantly changing net-centric systems and environment.

DoD acquisition professionals must recognize that the warfighter capabilities needed require software development techniques that differ significantly when compared to their commercially based counterparts. The software engineering techniques used in short-lived software products may not prove effective in developing long-lived DoD software-intensive, warfighting systems. DoD systems are designed to have a very long life span, including software-intensive systems, in direct contravention with most commercially based software designs. The need for OA design—upgradeable, flexible, and highly reliable software that is maintainable over a long life span—is paramount to DoD's warfighting systems, but industry-standard software engineering techniques do not necessarily incorporate those features as an industry-wide best practice.

What this means to the DoD is that the capabilities analysis and resulting system performance specifications must be completed in significantly more detail to achieve software performance that meets the warfighter's needs. The software developer needs to be driven to OA design by the WBS and performance specifications because software engineering discipline and state of the practice are unlikely to provide sufficient architectural designs without explicit performance

requirements clearly communicated. Providing more detailed performance specifications seems to run counter to acquisition reforms implemented to allow industry flexibility and innovation in achieving performance thresholds and goals, but that is not the intent. The detailed performance specifications provide the software developer much more information about areas that the customer—DoD—sees as critical to the overall system performance. This will have a significant impact on the system software design supporting OA performance and will provide the basis for a much more accurate cost and schedule estimate in the proposal received.

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Near-Term Challenges

The Global War on Terrorism (GWOT) continues to draw resources from the DoD transformation effort. *The National Military Strategy* explains, “Our challenge in the coming year and beyond is to stay the course as we continue to transform our Armed Forces to conduct future joint operations.”³ The wartime tempo consumes the operational life of existing systems much faster than the typical peacetime training tempo, driving the need to maintain and replace current technologies with resources that may have been applied to transformation. In addition, rapidly developed systems filling immediate needs, such as countering Improvised Explosive Devices (IEDs), compete for the same resources and usually produce interim systems that are not designed for integration into future net-centric systems, which are the cornerstones for DoD transformation.

The net-centric warfare concepts feature system-of-systems in an elaborate network requiring a significant number of critical interfaces. As each system is added or later upgrades its capabilities, it likely drives an interface change with other interfaced systems, necessitating the need for flexibility in accommodating interface changes from affected interoperating or networked systems. It is easy to visualize dozens of software changes driven by upgrades in the interfaced components of the network and the critical need for effective OA designs to quickly and economically accommodate change over a long life span. The required level of safety and security for networked warfighting systems exacerbates the OA design challenge, as OA-designed networks are inherently more difficult to secure. Again, this level of design flexibility is not a software industry norm for most commercially designed systems.

Safety and Security requirements for DoD weapon system software have few commercial counterparts. Obviously, commercially-based critical medical

³Chairman of the Joint Chiefs of Staff. *National Military Strategy of the United States of America* (2004), iv.

equipment, aviation systems, and banking systems would also require a high degree of safety and security, but the combat environment weapon systems are intended to operate within, and the military lives that are always at stake, add to criticality of the need. The net-centric warfare environment will necessarily require unprecedented security measures. Software must be designed to continue to operate critical weapon systems in degraded modes, reject spurious input without freezing or failing, and resist intrusion, viruses and other attacks. Anything short of that will put military members and the critical missions they perform at risk. Most commercially based software engineering disciplines do not consider such stringent safety and security requirements. The system's OA design must allow for the flexibility needed while simultaneously ensuring safety and security requirements. These two forces are rarely in concert and usually are in conflict.

Even without the additional challenges presented by the warfighting environment, successfully developing complex, software-intensive systems has been extremely problematic. "In a recent study of 250 software-intensive projects with 10,000 or more function points, only about 25 were deemed successful (i.e., achieved their initial cost, schedule and performance objectives)."⁴ In addition, the Government Accountability Office (at that time known as the General Accounting Office—GAO) reported that a 1999 study performed by the Standish Group concluded that the average cost overrun was 189 percent, the average schedule overrun was 222 percent, and only 61 percent of software-intensive programs delivered their originally specified features or functions.⁵ The DoD net-centric, system-of-systems development will certainly fall into this same category of software-intensive systems; and a success rate in the range of 10% is not acceptable. Clearly, each of the steps outlined in the Acquisition Essentials paragraph above must be scrutinized, analyzed, planned and intensively managed

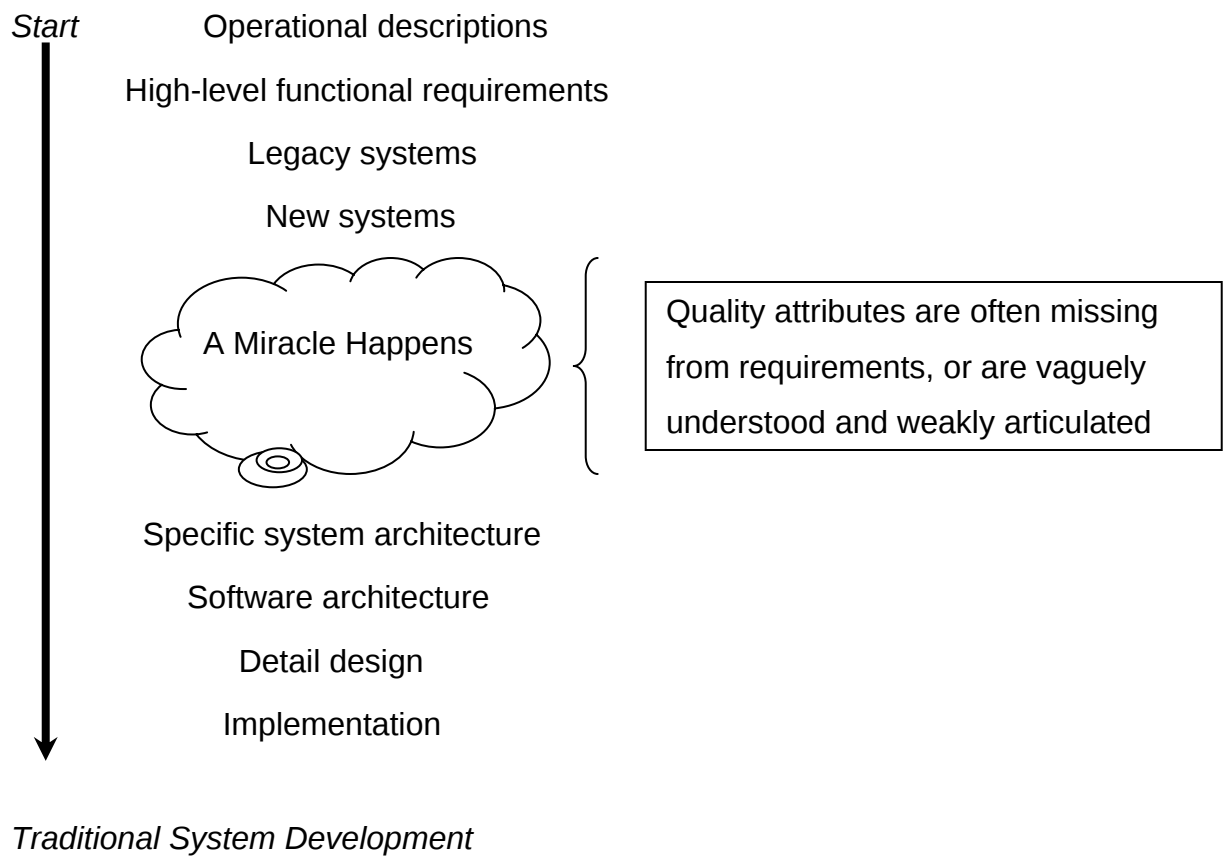
⁴ David Cottengim, "Irreducible Truths of Software-intensive Program Management," *Defense Acquisition Review Journal* 16, no. 1 (December 2005/March 2006): 393.

⁵ General Accounting Office, *Defense Acquisitions: Stronger management practices are needed to provide DoD's software-intensive weapon acquisitions*, Report to the Committee on Armed Service, US Senate. March 2004, publication no. GAO-04-393, 7.

to improve the probability of successfully delivering the warfighting capability needed, on time and within budget constraints.

From a software developer's point of view, there are further problems with the traditional system development model depicted below:⁶

Figure 1. Traditional System Development Model



From the software developer point of view, this *Traditional System Development* model obviously leaves a lot to be desired, but indicates the presence of a persistent and fatal flaw—lack of necessary information. If the requirements communicated via the WBS and Performance Specification are missing needed quality attributes or those attributes are vaguely understood and weakly articulated,

⁶ Mario R. Barbacci et al., *Quality Attribute Workshops (QAWs)*, 3rd ed. August 2003, CMU/SEI-2003-TR-016, 2.

a miracle will be needed to design and build the required software-intensive system. Requirements elicitation must be completed before the system can be designed and developed, so the developer must spend a significant amount of time and resources drawing missing requirements and gaining clarifications from the Government customer after award of the contract. That means that the real level of effort needed was not known at the time of the proposal or contract award, and proposed cost and schedule are likely to be significantly understated, immediately thrusting the program into a management crisis.

A more fully analyzed and developed WBS driving a more detailed Performance Specification help address the model deficiencies noted. The well-developed WBS provides the high-level functional design; the resulting Performance Specification must be analyzed and developed in such a way to include all necessary quality attributes articulated in clearly understood terms. The following analysis methodology provides a framework and process that will help provide software developers the necessary guidance to accurately propose, design and develop the capabilities needed by the warfighter within predictable and manageable resource limitations.

A Methodology for Software OA Capabilities Analysis

For DoD software-intensive systems to attain the broad spectrum of warfighter performance and long-term supportability with predictable costs and schedules, the Materiel Developer must provide performance specifications in the RFP that are detailed in areas that hardware-centric systems with mature engineering environments need not be. In addition to the system's software performance issues, the OA areas of Maintainability, Upgradeability, Interfaces/Interoperability, Reliability, Safety, and Security (MUIRSS) must be carefully analyzed to ensure the potential contractors understand the Government requirements and constraints in each of these areas. It is likely that the WBS will have to be developed several more levels deep in order to capture essential requirements; potential contractors would need to see such WBS development to form a realistic proposal with an executable schedule and an accurate cost estimate.

Work Breakdown System (WBS) Development Supporting Proposal Realism and Software Design

The Work Breakdown Structure (WBS) is a cornerstone for the Government "to structurally illustrate a clear understanding of the technical objectives and the end items or end products of the work to be performed by both Government and contract entities."⁷ The WBS serves as the system functional design description at the top levels and transitions to be the system's detail design at the lower levels. The Program WBS developed by the Materiel Developer conveys system functional elements considered critical for potential contractors to understand in order to build a system that is effective and suitable for the warfighter. This WBS Program level is very much a functional depiction of the system and is designed to provide potential

⁷ Department of Defense, *Department of Defense Handbook, "Work Breakdown Structures for Defense Materiel Items,"* 30 July 2005, MIL-HDBK-881A, 9.

contractors with a very good understanding of the level of effort needed to build the system.

For software-intensive systems, extending the program WBS development beyond Level 3 will be required to sufficiently convey details of performance necessary for prospective contractors to accurately estimate cost and schedule for a more realistic proposal. In part, this is driven by the net-centric and system-of-systems warfare concept, so the interfacing and network environments become a critical part of the WBS. The characterization of WBS Level 1 is transforming from an individual system description to a description of the network, as developed systems are part of larger network-centric and system-of-systems. "A SoS [system-of-systems] WBS is driven by the need to capture the common elements that support the integration of various systems into the SoS."⁸ The system-of-systems or network description becomes WBS Level 1 for all subsystems developed, and the WBS Level 3 provides very limited information regarding the functional design actually needed. In this environment, the WBS Level 3 was the previous generation's Level 2 as the network environment is correctly added on at the top level.

As the WBS is developed, it becomes the basis for system specifications. "This function includes developing the system specification, functional specifications, or a set of configuration items through requirements analysis, functional analysis and allocation, synthesis and systems analysis and controls."⁹ For the Program level of WBS, this clearly indicates that each WBS level is developed using a Systems Engineering Process (SEP) approach, eventually producing the essential system functions to be included in the performance specifications. These Performance Specifications are important portions of the Request for Proposal (RFP), providing critical information for potential contractors in formulating the proposed schedule and

⁸ Ibid., 7.

⁹ Ibid.

cost to develop and produce. The successful contractor will continue to develop the WBS into the detailed specifications that define the system architecture and design.

Proposal realism is linked with how clearly the RFP and integral Performance Specification convey the level of work necessary; likewise, the detail provided in the Performance Specification is linked with the Program WBS development. “A WBS can be expressed to any level. However, the top **three levels** are the minimum recommended any program or contract needs for reporting purposes unless the items identified are high cost or high risk. Then, and only then, is it critical to define the product at a lower level of WBS detail.”¹⁰ Software development within the immature engineering environment continues to be a risky process, and software-intensive systems are almost always high-cost, so consideration for developing supporting WBS below Level 3 should be automatic.

Considering the state of immature software engineering that exists today, it is clear the DoD will not achieve proposal realism nor the level of software-intensive system performance necessary if the WBS and performance specification are not developed more fully before hand-off to the developer or contractor. Due to the pressure to shorten the acquisition timeline, there is a tendency to rush the Request for Proposal (RFP) to the prospective contractors without developing the WBS below Level 3 or including the performance specification with sufficient detail. This approach works with systems based in mature engineering environments as the contractor understands that all of those unstated requirements will be satisfied through the established engineering standards; thus, the proposed schedule and cost estimates will be fairly accurate. With a software-intensive system, however, this is not the case due to many of the reasons presented earlier. The most diligent contractor can only provide cost and schedule estimates based on what is presented in the RFP. If a significant portion of the software development effort is not evident in the RFP, the contractor estimates may be grossly understated, causing

¹⁰ Ibid., 3.

substantial—and avoidable—funding shortfalls and schedule overruns that plague the development effort throughout the acquisition phase and well into the system's lifecycle.

MUIRSS Quality Attribute Analysis Technique

The Systems Engineering Process (SEP) is the preferred technique for analysis within each of the MUIRSS categories as it provides a highly structured and comprehensive methodology for developing the WBS. This will be a key tool for the DoD Materiel Developer in developing capabilities requirements and communicating them to the software developer via the performance specifications. Recognizing the existing shortfalls in software engineering maturity, this methodology will greatly assist the software developer in understanding OA-related performance requirements; this, in turn, will significantly influence the software architecture design and the level of effort estimated to build the desired system. The alternative leaves the software developer estimating these requirements without the background or experience to do so, or worse yet, discovering the extent of the actual requirements after the work has begun.

The capabilities analysis process must capture the OA performance needed for supporting the system throughout its lifecycle. This analysis should drive a robust Post Production Software Support (PPSS) plan and Computer Resources Life Cycle Management Plan (CRLCMP) addressing the MUIRSS elements of the OA design. The MUIRSS elements are interdependent and tend to apply across the system and software architecture. Each MUIRSS element is discussed in the following paragraphs to provide a basis for analyzing capability requirements within the area and capturing performance characteristics that are essential to the DoD.

Maintainability

The amount of elapsed time between initial fielding and the first required software maintenance action can probably be measured in hours, not days. The effectiveness and efficiency of these required maintenance actions is dependent on several factors, but the software architecture that was developed from the performance specifications provided is critical. The DoD must influence the software

architecture through the performance specification process to minimize the cost and time required to perform essential maintenance tasks.

Maintenance is one area where software is fundamentally different from hardware. Software is one of the very few components where we know that the fielded product has shortcomings, and we field it anyway. There are a number of reasons why this happens; for instance, there typically is not enough time, funding or resources to find and correct every error, glitch, or bug, and not every one is worth the effort of correcting. Knowing this, there must be a sound plan and resources immediately available to quickly correct those shortcomings that do surface during testing and especially those that arise during warfighting operations. Even when the system software is operating well, changes and upgrades in other, interfaced hardware and software systems will drive some sort of software maintenance action to the system software. In other words, there will be a continuous need for software maintenance in the planned complex system-of-systems architecture envisioned for net-centric warfare.

Because the frequency of required software maintenance actions is going to be much higher than in other systems, the cost to perform these tasks is likely to be higher as well. One of the reasons for this is that software is not maintained by "maintainers," as are most hardware systems, but is maintained by the same type of people that originally developed it—software engineers. These engineers will be needed immediately upon fielding, and a number will be needed throughout the lifespan of the system to perform maintenance, add capabilities, and upgrade the system. There are several models available to estimate the number of software engineers that will be needed for support; planning for funding these resources must begin very early in the process. As the DoD has a very limited capability for supporting software internally, typically, early software support is provided by the original developer and is included in the RFP and proposal for inclusion into the contract or as a follow-on Contractor Logistics Support (CLS) contract.

Upgradeability

A net-centric environment composed of numerous systems developed in an evolutionary acquisition model will create an environment of almost continuous change as each system upgrades its capabilities over time. System software will have to accommodate the changes and will have to, in turn, be upgraded to leverage the consistently added capabilities. The software architecture design will play a major role in how effective and efficient capabilities upgrades are implemented, so communicating the known, anticipated and likely system upgrades will impact how the software developer designs the software for known and unknown upgrades.

Trying to anticipate upgrade requirements for long-lived systems is extremely challenging to Materiel Developers, but is well worth their effort. Unanticipated software changes in the operational support phase cost 50 to 200 times the cost in early design; so, any software designed to accommodate an upgrade that is never realized costs virtually nothing when compared to changing software later for a capability that could have been anticipated. For example, the Army Tactical Missile System (ATACMS) Unitary was a requirement to modify the missile from warhead air delivery to surface detonation—that is, flying the warhead to the ground. The contract award was for \$119 million for the modification. The warhead was not new technology, nor particularly challenging to integrate with the missile body. The vast majority of this cost was to reengineer the software to guide the missile to the surface. Had there been an upgrade requirement for this type of mission in the original performance specification, this original cost (including potential upgrades, even if there were ten other upgrade requirements that were never applied) would have been a fraction of this modification cost.

Interfaces/Interoperability

OA design focuses on the strict control of interfaces to ensure the maximum flexibility in adding or changing system modules, whether they are hardware or software in nature. This presupposes that the system modules are known—which seems logical, as most hardware modules are well defined and bounded by both

physics and mature engineering standards. In sharp contrast to hardware, software modularity is not bounded by physics, and there are very few software industry standards for the modular architecture in software components. This is yet another area where the software developer needs much more information about operational, maintenance, reliability, safety and security performance requirements, as well as current, planned and potential system upgrades. These requirements, once well-defined and clearly communicated, will drive the developer to design a software modular architecture supporting OA performance goals. For example, if a system uses a Global Positioning System (GPS) signal, it is likely that the GPS will change over the life of the system. Knowing this, the software developer creates a corresponding discrete software module that is much easier and less expensive to interface, change and upgrade as the GPS system does so.

With the system software modular architecture developed, the focus returns to the interfaces between hardware and software modules, as well as to the external interfaces needed for the desired interoperability of the net-centric force. Software is, of course, one of the essential enablers for interoperability and provides a powerful tool for interfacing systems, including systems that were not designed to work together. Software performing the function of "middleware" allows legacy and other dissimilar systems to interoperate. Obviously, this interoperation provides a significant advantage, but comes with a cost in the form of maintainability, resources and system complexity. As software interfaces with other components and actually performs the interface function, controlling it and ensuring the interfaces provide the desired OA capability becomes a major software-management and software-discipline challenge.

One method being employed by the DoD attempts to control the critical interfaces through a set of parameters or protocols rather than active management of the network and network environment. This method falls short on several levels. It fails to understand and control the effects of aggregating all of the systems in a net-centric scheme. For instance, each individual system may meet all protocols for bandwidth, but when all systems are engaged on the network, all bandwidth

requirements are aggregated on the network—overloading the total bandwidth available for all systems. In addition, members of the Software Engineering Institute (SEI) noted:

While these standards may present a step in the right direction, they are limited in the extent to which they facilitate interoperability. At best, they define a minimal infrastructure that consists of products and other standards on which systems can be based. They do not define the common message semantics, operational protocols, and system execution scenarios that are needed for interoperation. They should not be considered system architectures. For example, the C4ISR domain-specific information (within the JTA) identifies acceptable standards for fiber channels and radio transmission interfaces, but does not specify the common semantics of messages to be communicated between C4ISR systems, nor does it define an architecture for a specific C4ISR system or set of systems.¹¹

Clearly, understanding and controlling the interfaces is critical for effective interoperation at both the system and system-of-systems levels. The individual program manager must actively manage all systems' interfaces impacting OA performance, and a network PM must do the same for the critical network interfaces. Due to this necessity of constant management, a parameters-and-protocols approach to net-centric OA performance is unlikely to produce the capabilities and functionality expected by the warfighter.

Understanding the software interfaces begins with the software architecture; controlling the interfaces is a unique challenge encompassing the need to integrate legacy and dissimilar systems and the lack of software interface standards within the existing software engineering environment. As stated earlier, the architecture needs to be driven through detailed performance specifications, which will help define the

¹¹ Edwin Morris et al., *System of Systems Interoperability (SOSI): Final Report* (Pittsburg, PA: Carnegie Mellon Software Engineering Institute, April 2004), 38.

interfaces to be controlled. An effective method for controlling the interfaces is to intensely manage a well-defined Interface Control Document (ICD), which should be a Contract Data Requirements List (CDRL) deliverable on any software-intensive or networked system.

Reliability

While the need for highly reliable weapon systems is obvious, the impact on total system reliability of integrating complex software components is not so obvious. Typically, as system complexity increases, maintaining system reliability becomes more of a challenge. Add the complexity of effectively networking a system-of-systems (all of which are individually complex) to a critical warfighting capability that is constantly evolving over time, and reliability becomes daunting.

Once again, the software developer must have an understanding of reliability requirements before crafting the software architecture and developing the software applications. Highly reliable systems often require redundant capability, and this holds true for software components as well. In addition, software problems tend to propagate, resulting in a degradation of system reliability over time. For example, a Malaysian Airlines Boeing 777 suffered several flight control problems resulting in: a near stall situation, contradicting instrument indications, false warnings, and difficulty controlling the aircraft in both autopilot and manual flight modes. The problem was traced to software in an air data inertial reference unit that was feeding erroneous data to the aircraft's primary flight computer (PFC), which is used in both autopilot and manual flight modes. The PFC continued to try to correct for the erroneous data received, adjusting flight control surfaces in all modes of flight, displaying indications that the aircraft was approaching stall speed and overspeed limits simultaneously, and causing wind shear alarms to sound close to landing.¹² It is critical for system reliability that the software developers understand how outputs from software

¹² Michael A. Dornheim, "A Wild Ride," *Aviation Week & Space Technology* 163 (September 2005): 46.

applications are used by interfaced systems so that appropriate reliability safeguards can be engineered into the developed software.

Software that freezes or shuts down the system when an anomaly occurs is certainly not reliable nor acceptable for critical weapon systems; yet, these characteristics are prevalent in commercially based software systems. Mission reliability is a function of the aggregation of the system's subcomponent reliability, so every software subcomponent is contributing to or detracting from that reliability. The complexity of software makes understanding all failure modes nearly impossible, but there are many techniques that software developers can employ when designing the architecture and engineering the applications to improve the software component reliability. Once requirements are clearly communicated to the developers, the software can be engineered with redundancy or "safe mode" capabilities to vastly improve mission reliability when anomalies occur. The key is identifying the reliability requirements and making them clear to the software developers.

Safety

Very few software applications have the required safety margins associated with critical weapon systems used by warfighters in combat situations—where they are depending on these margins for their survival. Typically, the software developers have only a vague idea of what their software is doing and how critical that function is to the warfighter employing the weapon system. Safety performance must be communicated to the software developers from the beginning of development so they have the link between software functionality and systems safety. For example, suppose a smart munition senses that it does not have control of a critical directional component, and it calculates that it cannot hit the intended target. The next set of instructions the software provides to the malfunctioning system may well be critical to the safety of friendly troops, so software developers must have the necessary understanding of operational safety to decide how to code the software for what will happen next.

Software safety is clearly linked with reliability, as software that is more reliable is inherently safer. It is critical that the software developer understands how the warfighter expects the software to operate in abnormal situations, degraded modes, and when inputs are outside of expected values. Much commercially based software simply ceases to function under these conditions or gives error messages that supercede whatever function was being performed, none of which are acceptable in combat operations.

Security

With software performing so many critical functions, there is little doubt that software applications are a prime target for anyone opposing US and Allied forces. Critical weapon system and networking software must be resistant to hacking, spoofing, mimicking, and all other manner of attack. There must be capabilities of isolating attacks and portions of networks that have been compromised without losing the ability to continue operations in critical combat situations. The software developer must know all these capabilities are essential before he/she constructs software architectures and software programs, as this knowledge will be very influential for the software design and application development. Software Engineering Institute's *Quality Attribute Workshop* states, "As an example, consider security. It is difficult, maybe even impossible, to add effective security to a system as an afterthought. Component as well as communication mechanisms and paths must be designed or selected early in the lifecycle to satisfy security requirements."¹³

Interoperability challenges are increased when the system-of-systems have the type of security requirements needed by the DoD. Legacy systems and existing security protocols will likely need to be considered before other security architecture can be effectively designed. OA capabilities will be hampered by the critical need for security; both must be carefully balanced to optimize system performance and

¹³ Mario R. Barbacci et al., *Quality Attribute Workshops (QAWs)*, 3rd ed. August 2003, CMU/SEI-2003-TR-016, 2.

security. This balance of OA and security must be managed by the DoD and not the software developer.

Physical security schemes and operating procedures will also have an impact on the software architecture. For example, many communication security (COMSEC) devices need only routine security until the keys, usually software programs, are applied; then, much more stringent security procedures are implemented. Knowledge of this security feature would be a key requirement of the developer; he/she must understand how and when the critical software pieces are uploaded to the COMSEC device. The same holds true for weapon systems that upload sensitive mission data just prior to launch.

Residual software on equipment or munitions that could fall into enemy hands presents another type of security challenge that needs to be addressed during the application development. For example, the ATACMS missile air-delivers some of its warheads, leaving the missile body to freefall to the surface. It is very conceivable that the body could be intact and, of course, unsecured. If critical mission software was still within the body and found by enemy forces, valuable information may be gleaned from knowing how the system finds its targets. We would certainly want the developer to design the applications in a way that would make anything recovered useless to the enemy, but this is a capability that is not intuitive to the software developers.

Network Development

The network is a lynchpin for the combat effectiveness of NCW architecture, and as such, should be developed under a professional Program Management (PM) organization. The US Navy has achieved optimal results by assigning a PM for the Link 16 Program as noted by SEI: “The Navy created a PMO and funded it with money from affected programs. These monies were returned to programs specifically to work toward Link 16 capability.”¹⁴ SEI goes on to describe the need

¹⁴ Edwin Morris et al., *System of Systems Interoperability (SOSI): Final Report* (Pittsburg, PA: Carnegie Mellon Software Engineering Institute, April 2004), 33.

for professional program management by stating, “What is needed are processes that help to reach agreements, blinders that avoid getting distracted by things that are not related (e.g., portability), and to be agnostic about specific technologies (e.g., CORBA or Message Oriented Middleware).”¹⁵ A network PM would help facilitate and broker those agreements to the benefit of the network, vastly increasing the probability that the NCW asset will provide the warfighter the capability and advantage visualized by DoD.

¹⁵ Ibid., 34.

Summary

To get the needed Open Architecture performance the DoD is seeking for software components, the Material developer will have to specify it in the RFP and Performance Specification. Unlike many hardware-centric engineering environments, the immature software engineering environment is unlikely to compensate for essential performance that is not specified. With the Materiel Developer performing the capabilities analysis using the MUIRSS approach outlined above, the potential software developers will be provided a much more detailed understanding of critical capabilities the DoD expects from its software components.

This same technique should result in significantly more accurate proposals as much more of the software development work can be estimated from the RFP and Performance Specification provided. Yes, proposals will likely continue to be overly optimistic, especially in a competitive environment. And yes, changes and details will still be revealed after the contract is signed—but the cost growth should be in the range of ten percent of the cost, not the current average of one-hundred percent of the original proposal. Schedule estimates will also be much more accurate as the scope of the software work is better understood by the contractors, keeping schedule slippage to under fifteen percent of the original proposal estimate.

Conducting this analysis will be as challenging as it is time-consuming, especially since it is applied in the early stages of the acquisition process when there is great pressure to “get the RFP on the street.” Yet, the enormous potential time and cost savings realized throughout the remaining development and the system’s lifecycle by completing the thorough MUIRSS capability analysis warrants the needed analysis time. There is an old carpenter’s adage that applies well in this case: “measure twice, cut once.”

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