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A Publication of the Defense Acquisition University

"... All Others Must Bring Data."

— W. Edwards Deming

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CONTENTS | Featured Research

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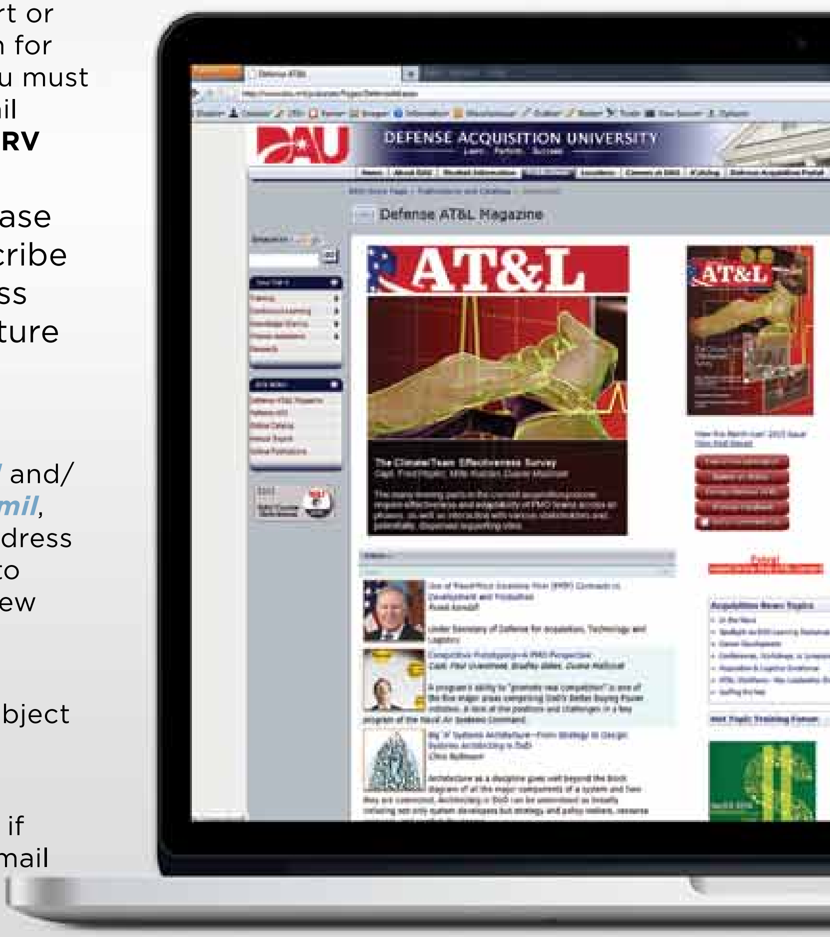

From the Chairman and Executive Editor

The theme for this edition of *Defense Acquisition Research Journal* is "...All Others Must Bring Data." It derives from the famous quote by American management consultant W. Edwards Deming, "In God we trust; all others must bring data," displayed outside the office of Under Secretary of Defense for Acquisition, Technology, and Logistics Frank Kendall. Accurate and meaningful data are the basis for making informed acquisition policy decisions; as British scientist William Thomson (Lord Kelvin) said over a century ago, "When you can measure what you are speaking about ... you know something about it; but when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind."*

The first article, "Compressing Test and Evaluation by Using Flow Data for Scalable Network Traffic Analysis," by Kevin Buell, Mustafa G. Baydogan, Burhan Senturk, and James P. Kerr, examines one method for accelerating the test and evaluation phase for data network-based programs by using readily scalable flow data. The second article, "Improving Statistical Rigor in Defense Test and Evaluation: Use of Tolerance Intervals in Designed Experiments," by Alethea Rucker, looks at statistical tolerance intervals in designed experiments as an analysis method for the Department of Defense test and evaluation technical community.

In "A Comparative Analysis of the Value of Technology Readiness Assessments," Reginald U. Bailey, Thomas A. Mazzuchi, Shahram Sarkani, and David F. Rico provide a comparative analysis and model of the economic value of Technology Readiness Assessments for major defense acquisition programs. Finally, Holly A. H. Handley and Beverly G. Knapp ask "Where Are the People? The Human Viewpoint Approach for

Architecting and Acquisition," arguing that the Department of Defense Architecture Framework needs a more robust link between the system architecting and the Human Systems Integration communities.

The featured book in this issue's Defense Acquisition Professional Reading List is Volume II in the History of Acquisition in the Department of Defense series, *Adapting to Flexible Response, 1960-1968,* by Walter S. Poole. The reviewer is Dr. Roy L. Wood, dean of DAU's Defense Systems Management College.

Finally, I encourage prospective authors to consider submitting their manuscripts for the DAU Alumni Association's 2015 Acquisition Symposium, following the guidelines in the Call for Papers in this issue.

Dr. Larrie D. Ferreiro
Executive Editor
Defense ARJ

* Thomson, W. (1889). Lecture on electrical units of measurement. *Popular Lectures* (Vol. I). London: MacMillan.

The full quote is:

> I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science, whatever the matter may be. (p. 73)


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DAU ALUMNI ASSOCIATION

2015 HIRSCH RESEARCH PAPER COMPETITION

CALL FOR PAPERS

Research topics may include:

- Improve Professionalism of the Total Acquisition Workforce
- Career Path and Incentives
- Agile Program Management
- Incorporating Foreign Military Sales and Direct Contractor Sales Strategies into Programs
- Controlling Costs Throughout the Product Life Cycle
- System Cyber Hardness

GROUND RULES

- The competition is open to anyone interested in the DoD acquisition system and is not limited to government or contractor personnel.
- Employees of the federal government (including military personnel) are encouraged to compete and are eligible for cash awards unless the paper was researched or written as part of the employee's official duties or was done on government time. If the research effort is performed as part of official duties or on government time, the employee is eligible for a noncash prize, i.e., certificate and donation of cash prize to a Combined Federal Campaign registered charity of winner's choice.
- First prize is $1,000. Second prize is $500.
- The format of the paper must be in accordance with guidelines for articles submitted for the *Defense Acquisition Research Journal*.
- Papers are to be submitted to the DAU Director of Research: research@dau.mil.
- Papers will be evaluated by a panel selected by the DAUAA Board of Directors and the DAU Director of Research.
- Award winners will present their papers at the DAU Acquisition Community Training Symposium, Tuesday, April 7, 2015, at the DAU Fort Belvoir campus.
- Papers must be submitted by December 16, 2014, and awards will be announced in January 2015.

DAU Center for Defense Acquisition Research

Research Agenda 2015-2016

The Defense Acquisition Research Agenda is intended to make researchers aware of the topics that are, or should be, of particular concern to the broader defense acquisition community throughout the government, academic, and industrial sectors. The purpose of conducting research in these areas is to provide solid, empirically based findings to create a broad body of knowledge that can inform the development of policies, procedures, and processes in defense acquisition, and to help shape the thought leadership for the acquisition community.

Each issue of the *Defense ARJ* will include a different selection of research topics from the overall agenda, which is at: *http://www.dau.mil/research/Pages/researchareas.aspx*

Measuring the Effects of Competition

- What means are there (or can be developed) to measure the effect on defense acquisition costs of maintaining an industrial base in various sectors?
- What means exist (or can be developed) of measuring the effect of utilizing defense industrial infrastructure for commercial manufacture in growth industries? In other words, can we measure the effect of using defense manufacturing to expand the buyer base?
- What means exist (or can be developed) to determine the degree of openness that exists in competitive awards?
- What are the different effects of the two best-value source-selection processes (tradeoff vs. lowest price technically acceptable) on program cost, schedule, and performance?

Strategic Competition

- Is there evidence that competition between system portfolios is an effective means of controlling price and costs?
- Does lack of competition automatically mean higher prices? For example, is there evidence that sole source can result in lower overall administrative costs at both the government and industry levels, to the effect of lowering total costs?
- What are the long-term historical trends for competition guidance and practice in defense acquisition policies and practices?
- To what extent are contracts being awarded noncompetitively by congressional mandate, for policy interest reasons? What is the effect on contract price and performance?
- What means are there (or can be developed) to determine the degree to which competitive program costs are negatively affected by laws and regulations such as the Berry Amendment and Buy America Acts?

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Compressing Test and Evaluation by Using Flow Data for Scalable Network Traffic Analysis

Kevin Buell, Mustafa G. Baydogan, Burhan Senturk, and James P. Kerr

The specialized nature of technology-based programs creates volumes of data on a magnitude never before seen, complicating the test and evaluation phase of acquisition. This article provides a practical solution for reducing network traffic analysis data while expediting test and evaluation. From small lab testing to full integration test events, quality of service and other key metrics of military systems and networks are evaluated. Network data captured in standard flow formats enable scalable approaches for producing network traffic analyses. Because of its compact representation of network traffic, flow data naturally scale well. Some analyses require deep packet inspection, but many can be calculated/approximated quickly with flow data, including quality-of-service metrics like completion rate and speed of service.

« *Image designed by Diane Fleischer*

1

Challenges for Acquisition

With two major conflicts coming to an end—Iraq in late 2011 and the expected end of U.S.-led combat operations this year in Afghanistan—it comes as little surprise that budgets throughout the Department of Defense are entering an age of austerity. The earlier enacted across-the-board federal spending cuts, known as sequestration, claimed a percentage of the Defense Department's budget. Despite these budget cuts, the expectation that defense acquisition professionals will field technology-based systems to the warfighter is at an all-time high. Low-intensity conflict operations throughout the world rely heavily on technology and intelligence systems.

Complicating the acquisition of these technology-based systems and programs is the voluminous amounts of data they produce, as observed at the Army's recurring large technology test event, the Network Integrated Evaluation (NIE). NIE produces terabytes of network data in a single day; this amount of data is simply too large to manage and far too large for test and evaluation (T&E) professionals to efficiently analyze the data. Processing a single data set can take as long as 24 to 36 hours; the status quo is grossly inefficient to meet the needs of rapid acquisition.

Because of these inefficiencies, meaningful and effective engineering modifications performed during a test event cannot be done fast enough. The delay between analysis, engineering modifications based on data, and validation can extend the test event—or worse, necessitate a follow-on event. Both scenarios require a longer T&E phase whether in developmental test, operational test, or integrated test, which impacts schedule and cost by extending the T&E phase of the acquisition life cycle. Moving programs that involve complex information and communication networks from the Technology Development Phase (Milestone B) to the Engineering & Manufacturing Development phase of the Integrated Defense Acquisition, Technology and Logistics Life Cycle Management System (Cochrane & Brown, 2010) is notoriously difficult for a variety of reasons, not the least of which is inefficient methods of handling T&E data.

Engineers from the U.S. Army Electronic Proving Ground, with their academic partners at Arizona State University's Security and Defense Systems Initiative, developed a way to compress some of the T&E timeline for defense technology systems that use networks. This partnership realized nominal gains of 75 percent, reducing analysis time from 24 hours to as little as six for data sets of approximately two terabytes. The efficiency gains are a sum of statistical and probabilistic modeling, data reduction, and the use of commercial-off-the-shelf software (COTS) for analyzing network traffic. These gains are a partial answer to the challenge introduced at the beginning of this article: that defense acquisition professionals must manage to field capable technology systems to the warfighter.

Background

Analysis of network traffic has been studied for some time, and a well-established body of research exists on Internet measurement (Crovella & Krishnamurthy, 2006). However, evaluation of networks within military test exercises has some unique characteristics not shared with general Internet measurement. For example, while Internet measurement is largely focused on collecting data at routers, military test exercises often focus more on collecting data at end-nodes. In some ways, this is a luxury enabled by the contained evaluation environment, which allows for accurate point-to-point metrics like speed of service.

On the other hand, collecting data at end-nodes can account only for traffic seen on those nodes. The network may not be large enough for router-based measurements to be useful, so end-node collection may be the only option. This unique environment is not well explored in the current literature on Internet measurement.

Military test exercises present further challenges. Because of the nature of field exercises, harvesting data may not occur as frequently as test officers would like. Interfaces and protocols may not be in place to gather test data, and it often must be copied and physically carried from nodes under test. These unique aspects can lead to data collection inconsistencies and errors.

Nevertheless, providing access to measurement results is essential for providing information that may affect ongoing testing. For example, determining whether a data collection system is working, whether a node is active, and how much data has been collected are all important to know as soon as possible during testing.

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As the amount of data flowing over networks increases, the ability to collect, transfer, store, process, and analyze the data becomes more challenging. Many tools and standards from the Internet measurement community can be useful here. Where possible, using open-source software is preferable, thereby decreasing costs and avoiding "reinventing the wheel." Using standard data formats is pivotal to knowledge transfer and tool interoperability. When compared to solutions developed in-house, the open source solution often offers greater performance, and a larger support community, and it is typically far less costly.

As the amount of data flowing over networks increases, the ability to collect, transfer, store, process, and analyze the data becomes more challenging.

Traffic Data Formats

To record network traffic, two main formats are generally available: packet capture and flow. Packet capture formats record everything that goes across the wire (each individual packet, including header and data). Flow formats summarize the traffic and exclude the content. Excluding the content sacrifices the ability to reconstruct true network traffic. However, focusing on flow formats allows for important metrics about the network traffic—like performance, quality of service, and loss—but alleviates the burden of fully constituted packets.

Flow formats are attractive because working with large sizes of data presents bottlenecks, particularly with disk reads and writes. Smaller data sizes result in faster analysis performance. The most popular flow format has been NetFlow from Cisco, but it has been standardized into a nonproprietary flow format called Internet Protocol (IP) Flow Information Export, or IPFIX (Internet Engineering Task Force, n.d.), and several other flow formats are precursors or variations on the flow concept.

Flows normally summarize traffic by recording the number of packets, total bytes, flags, protocols, and other elements over some time period (e.g., 1 minute) from a source IP address to a destination IP address. These are referred to as aggregated flows. An alternative is to produce one flow per packet, referred to as single-packet flows. These enable some quality-of-service and other advanced analyses discussed later.

Some tools also work natively with flow data that have been compressed using standard compression algorithms. Table 1 represents a sample calculation based on various observations when working with flow data. Exact numbers will vary based on traffic characteristics, but this gives some idea of the significant data reduction achieved when using flow data, which in turn eliminates the disk throughput bottleneck.

TABLE 1. SAMPLE FLOW SIZES FOR A GIVEN SET OF PACKET CAPTURES

	Packet Capture	Single-Packet Flow	Single-Packet Flow (Compressed)	Aggregated Flow	Aggregated Flow (compressed)
Size	500 GB	38 GB	2 GB	0.25 GB	0.04 GB

Data Preparation

Network traffic data must be collected and prepared for analysis to support real-time queries and in-depth discovery. Ideally, traffic data are collected natively in flow format (such capabilities are built into most routers). Since some applications require full packet contents, other approaches may be required, such as capturing full packet data and producing flows from it or capturing both full packet and flow data simultaneously.

Reading packet capture data is normally bounded by disk I/O (input/output), but writing it to the significantly smaller flow format is generally not. Optimized open source tools like Yet Another Framework, or YAF (Software Engineering Institute, 2006), convert standard Libpcap-formatted packet captures (Libpcap is a portable library for network traffic capture) to IPFIX format. Conversion time is largely a product of disk read speed. For example, on a current commodity system with

100MB/s read speed, conversions performed from packet capture to flow took about 11 seconds/GB. This means that converting 500GB of packet capture would take about 1.5 hours.

Generally, two approaches are used to produce a final set of flow data. For analyses that do not compare traffic between two traffic collection points (e.g., traffic load, protocol distribution, topology), the following steps are required:

1. Convert all packet capture files to aggregated flow files.
2. Combine the aggregated flow files into a single aggregated flow file.
3. Deduplicate the single aggregated flow file.

The final flow file is deduplicated to avoid double counting traffic seen at a source and destination traffic collection point. An accurate (but approximated) deduplication process is available in some flow-based tools and is accomplished by matching flows based on time, protocol, bytes, and so on within a configurable threshold.

For analyses based on matching packets between traffic collection points (e.g., completion rate, speed of service), the following steps are required:

1. Convert all packet capture files to single packet flow files.
2. Combine the single packet flow files producing one flow file per traffic collection point.

The resulting files are not deduplicated to enable matching of traffic between files for these types of analyses.

Traffic Analysis

An extensive search and evaluation of open source network traffic analysis tools yields several that are particularly noteworthy and useful. Of course, Wireshark and tshark are popular tools providing packet inspection capabilities (Wireshark, n.d.), but their performance in many respects is lacking, particularly for processing many large files. A library called libtrace provides optimal results for working with packet capture files (WAND Network Research Group, n.d.). Argus is another open source tool that provides significant functionality as well as a proprietary flow format that includes some additional information that could be useful for characterizing traffic (QoSient, 2014).

One noteworthy tool that is well-supported, highly optimized, and contains all the basic functionality one would expect for data preparation and traffic analysis is SiLK (Software Engineering Institute, 2006). Traffic analyses enabled by aggregated flow files using SiLK queries include (but are not limited to):

- Topology by generating lists of source/destination pairs;
- Finding all traffic communicating on a given port;
- Separating nodes or pairs into bins based on percentage of total load; and
- Configurable filtering and traffic identification based on any combination of port, protocol, IP address, flow start/end/duration, etc.

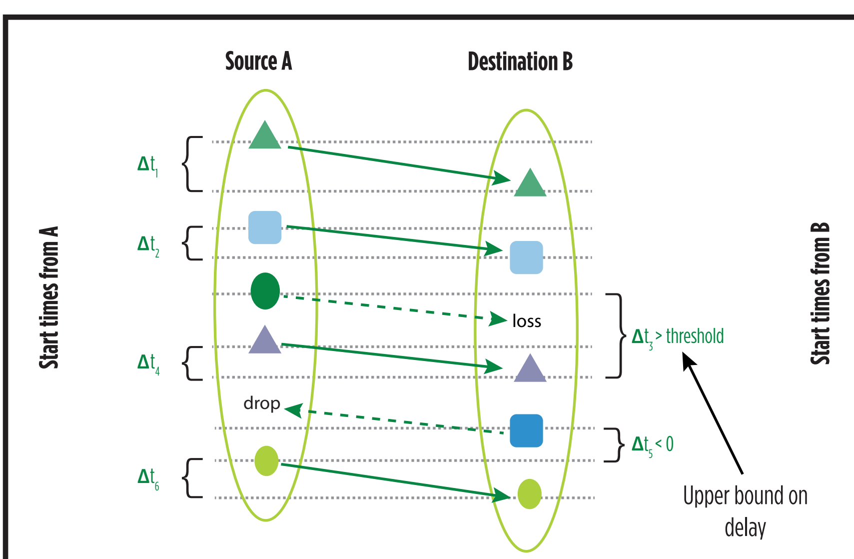
Visualization is not the focus of this article, but two open source tools should be mentioned here. The Ozone Widget Framework (Next Century, n.d.) has proven to be very useful. Also, an extensive, clean, and optimized JavaScript library for visualizing many types of data can be found in D3–Data Driven Documents (Bostock, 2013).

Quality of Service from Flow

Two essential metrics of network traffic are delay and loss. Delay is sometimes referred to as speed of service and loss is sometimes measured by completion rate. Given two files of single-packet flows representing two traffic collection points—each of which is associated with one or more nodes—the traffic loss between the two is determined by simply adding the number of packets in the file representing the destination, and then subtracting the number of packets in the source.

Calculating delay is generally more complicated and subject to some error with flow data. Using files from two traffic collection points, packets can be matched based on characteristics like size and protocol, as well as timestamp within a given threshold as shown in Figure 1. The time-stamps for a given packet will be different in the source and destination precisely because of delay.

FIGURE 1. DELAY AND LOSS BETWEEN SENDER AND RECEIVER



For a given source IP and destination IP pair, reading all single packet flows into memory and matching packets is feasible. To calculate the speed of service, simply subtract the timestamp of the matched packet in the source from that in the destination, and then average the difference over all the matched pairs. This is not matching packets based on content, and working with a timestamp threshold for matching will produce some error. However, packet matching with only flow data—when compared with matching using full packet content—provides nearly identical results.

Two essential metrics of network traffic are delay and loss.

In fact, the average delay over some number of packets (versus delay for an individual packet) can be calculated accurately using a number of approaches. Though lost packets must be accounted for, matching each packet precisely is not essential to produce an accurate average. Instead, ensure that packets are simply matched (uniquely) with some nearby packet in the source and destination. Mathematically, this is because (b1 – a1) + (b2 – a2) is identical to (b1 – a2) + (b2 – a1). In fact, and if it appears more computationally feasible, an alternative is to add all timestamps over a given period from the destination, and then subtract the corresponding timestamps from the source, i.e., (b1 + b2) – (a1 + a2). After dividing by the number of packets, the resultant average delay is the same as exact pairwise matching.

Since flow formats generally provide for some extensibility, one approach to improve matching accuracy is to compute a reasonable, locally unique hash value per packet based on its contents. This hash value is stored as additional information within the flow record. Indeed, flow extensibility can be an important means of bridging the gap between full packet capture and flow data by allowing for small, but critical pieces of data from some packets to be stored with flow records.

Future Work

Some analyses, which are now only accomplished using packet capture data could be accomplished using flow data, but may require some statistical analysis or algorithmic development. For example, reporting quality of service based on message type (e.g., voice versus video versus Web document) might normally require deep packet inspection. However, a flow format could save an indication of message type when converting from packet capture to flow, using extensibility. Also, traffic application mining has been studied extensively and could be used on flows to add some information about message/application type.

Many statistical approaches are available that could provide value in this domain. Finding cause/effect of poor network conditions, finding anomalies, and other problems could be solved with statistical data mining approaches. For example, low quality of service may be caused by many factors including high traffic volume (and associated congestion), proximity of sender and receiver, or physical conditions such as obstacles in the path between sender and receiver.

Advanced analyses may also highlight where significant events occur and which nodes are involved in these events. They may include ways to group and visualize nodes beyond standard clustering like logical topology and geographical display. Node groups may instead be formed based on traffic profile matching and/or quality-of-service similarities.

Conclusions

As the volume of network traffic data increases, analysis of military systems and networks becomes more challenging. Flow data have been used by the general Internet measurement community for some time to enable scalable traffic analysis for cyber security and traffic engineering. However, flow data have not been widely applied to metrics requiring more precision and advanced analytics. Military exercises are unique in that they are generally a smaller, contained set of traffic, often utilizing end-to-end measurements.

Flow data are much smaller than full packet captures and thus address the I/O bottleneck common in data processing for network measurement. Compressed flows provide even more data minimization. Common flow formats allow for some extensibility so that essential pieces of payload can be kept within a flow when needed.

Traffic flow data directly enable basic traffic characterizations like load and protocol distribution, and these are handled well by open source tools that work with flow data. More advanced analyses like quality of service are also possible using flow data and flow tools with additional algorithmic support. By capturing flows composed of a single packet and matching these flows at source and destination, delay and packet loss can be calculated accurately using flow data.

Statistical approaches could be used for even more high-level traffic characterization such as cause/effect analysis of network traffic conditions. Advanced analyses may also highlight where significant events occur and which nodes are involved in these events. Grouping nodes based not only on logical topology and physical location, but also traffic pattern similarity would also provide additional understanding and enhanced visual analytics. These provide greater insight into network traffic data that can point operators to potential areas for further analysis.

These approaches to increase the efficiency of network traffic analysis are small, but indicative of the trend to meet the big data problem. The length of T&E for technology-based programs will continue to grow as the complexity and interdependencies of these systems grow. The challenge of big data can be mitigated through incremental improvements. Using sensible, pragmatic methods that reduce the data—through statistical and probabilistic modeling coupled with the acceleration of analysis by adopting COTS—is one way to manage this big data challenge. Regardless of the challenge, defense acquisition professionals must look for new ways to enable our increasingly technology-enhanced warfighter.

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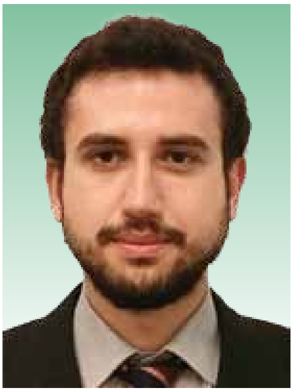
Author Biographies

Dr. Kevin Buell is a research scientist at Arizona State University Research Enterprise (ASURE) in Scottsdale, AZ. His work focuses on network analysis, cyber security, and software engineering. He received his PhD in computer science from Arizona State University and has an extensive background in software engineering for the defense industry. Dr. Buell is a member of the Institute for Electrical and Electronics Engineers Computer Society as well as ACM's Special Interest Group on Software Engineering.

(E-mail address: kevin.buell@asu.edu)

Dr. Mustafa Baydogan is a postdoctoral Fellow at Arizona State University's Security and Defense Systems Initiative. He received his PhD in industrial engineering from Arizona State University and specializes in data mining and statistical process control. Dr. Baydogan is an active member of the data mining section of the Institute for Operations Research and the Management Sciences.

(E-mail address: mustafa.baydogan@asu.edu)



Mr. Burhan Senturk is a master's student in the School of Computing, Informatics, and Decision Systems Engineering at Arizona State University. He received his BS in computer science from Middle Eastern Technical University. Mr. Senturk's work is focused on data mining and network traffic analysis.

(E-mail address: muhammet.senturk@asu.edu)

Mr. James P. Kerr is a computer scientist at the U.S. Army Electronic Proving Ground at Fort Huachuca, AZ. He specializes in instrumentation development and support for network test and evaluation. He is currently working on next-generation tools and infrastructure for large-scale test events. Mr. Kerr received his MA in mathematics at San Diego State University.

(E-mail address: james.p.kerr.civ@mail.mil)

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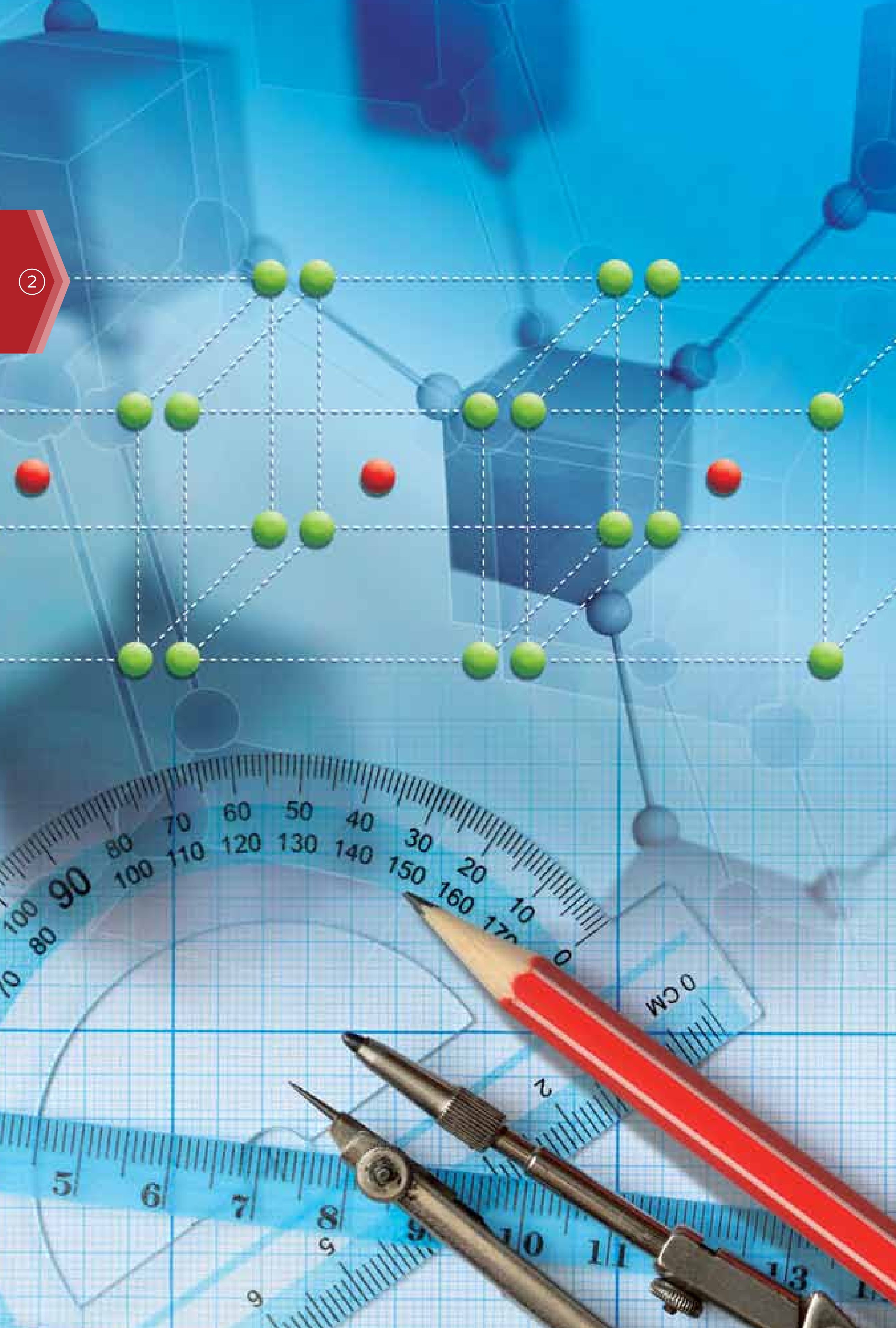

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Keywords: *Test and Evaluation, Scientific Test and Analysis Techniques, Design of Experiments, Tolerance Intervals, Statistics*

Improving Statistical Rigor in Defense Test and Evaluation: *Use of Tolerance Intervals in Designed Experiments*

Alethea Rucker

Leveraging the use of statistical methods is critical in providing defensible test data to the Department of Defense Test and Evaluation (T&E) enterprise. This article investigates statistical tolerance intervals in designed experiments for the T&E technical community. Tolerance intervals are scarcely discussed in extant literature as compared to confidence/prediction intervals. The lesser known tolerance intervals can ensure a proportion of the population is captured in the design space, and have the ability to map the design space where factors can be reliably tested. Further, the article investigates several two-sided approximate tolerance factors estimated by Monte Carlo simulation and compares them to the exact method. Finally, the applicability of tolerance intervals to the defense T&E community is presented using a simple case study.

« Image designed by Diane Fleischer

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In the FY 2012 Annual Report from the Director, Operational Test and Evaluation (DOT&E), the director identified two areas as requiring further improvement to move toward institutionalizing statistical rigor: (a) "execution of testing in accordance with the planned test design" and (b) "analysis of test data using advanced statistical methods commensurate with test designs developed using DOE [Design of Experiments]" (Gilmore, 2012a, p. v). The report further states that current data analysis is "limited to reporting a single average (mean) of the performance across all the test conditions" (p. v). In doing so, efficiencies achieved through meticulous test planning and design are discarded. Realizing the need for increased rigor, a Defense Science of Test Research Consortium was formed in 2011, partnered with Arizona State University, Virginia Polytechnic Institute and State University, Naval Postgraduate School, and the Air Force Institute of Technology (AFIT). The consortium's overall research goal is to support the incorporation of advanced statistical rigor and mathematical foundations into the test enterprise (AFIT, 2012). Research largely focuses on improved experimental design and statistical theory (Freeman, Ryan, Kensler, Dickinson & Vining, 2013; Haase, Hill, & Hodson, 2011; Hill, Gutman, Chambal, & Kitchen, 2013; Johnson, Hutto, Simpson, & Montgomery, 2012). The research of tolerance intervals in designed experiments has yet to be fully discussed. This article continues the research dialogue and adds to the body of knowledge of tolerance interval literature in defense testing, particularly the Scientific Test and Analysis Techniques (STAT) implementation effort. Further, this article aims to assist primarily test and evaluation (T&E) practitioners such as engineers, analysts, and test project/program managers in understanding how the use of statistics can greatly improve the quality of results in the decision-making process and improve credibility through objective data.

Purpose

The purpose of this article is twofold. First, tolerance intervals are rarely discussed in extant literature as having application to the defense T&E community. This research closes the gap by exploring the applicability of tolerance intervals in designed experiments. An attempt to use tolerance intervals in defense testing was investigated by the National Research Council (NRC) of the National Academies on testing body armor materials. Their recently published work (NRC, 2012) recommended use of statistical tolerance bounds, but their examples were confined to single, normally distributed samples, and did not take into account the design structure. Second, increased statistical rigor is needed in defense testing and analysis due to the complexity and challenges in testing a defense weapon system. Recently, the use of STAT has gained traction within the Department of Defense (DoD) T&E community (DoD, 2012; Gilmore, 2010; Operational Test Agencies, 2009). Albeit gradual, the defense community is leveraging the long-spanning, rich history of statistical methods in industry and replacing the budget-driven test events, combat scenarios, and one-factor-at-a-time approach with a statisticaly rigorous approach to test design using DOE (Johnson et al., 2012). Though current guidance and emphasis on the use of designed experiments in test plans is sufficient in explaining test planning and design, it falls short of providing specific guidance on test analysis and reporting to the decision makers, who ultimately decide on whether to field the weapon system to the warfighter. In these resource-constrained times, providing the T&E community defensible and objective test data to enable risk management for leadership during system development, procurement, and operation is imperative.

Increased statistical rigor is needed in defense testing and analysis due to the complexity and challenges in testing a defense weapon system.

What Are Tolerance Intervals?

The importance of tolerance intervals has long been recognized (Wilks, 1941, 1942), with wide applicability to areas such as manufacturing, pharmaceutical, quality control, engineering, and material science commonly referred to as A- and B-basis allowables. In general, tolerance intervals capture a fixed proportion of population (p) with a given confidence level (1-α). Confidence intervals are the most commonly used statistical interval method focused on parameters such as mean and/or standard deviation, while prediction intervals consider the prediction of individual responses. Prediction intervals are useful only if the sample on which the interval is based represents the population, but if the population changes over time, then the prediction interval is useless (Vining, 1997). In other practical instances, the proportion of population, rather than mean is of interest, rendering tolerance intervals more appropriately applied in those situations. A tolerance interval allows

2

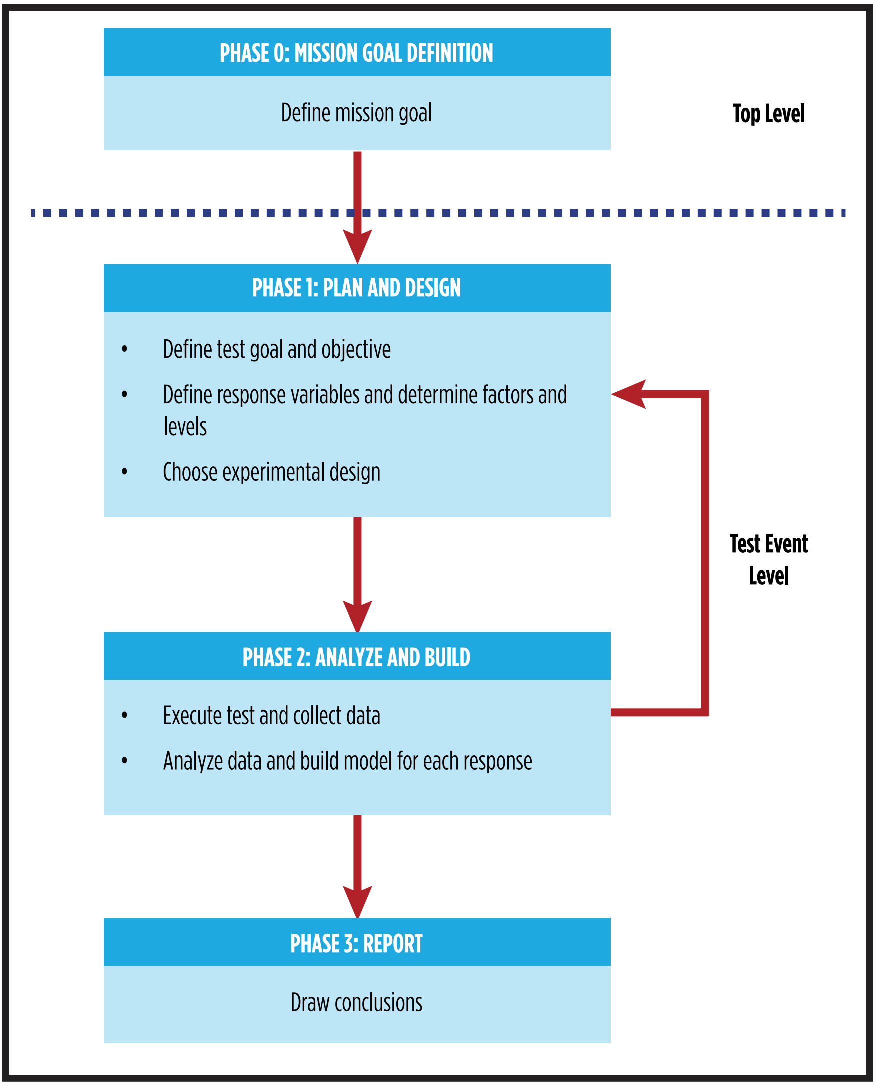
us to make statements surrounding the distribution rather than the predicted individual responses, such as: "We are 95 percent confident that at least 90 percent of the population distribution will lie within the specified interval." Unfortunately, tolerance intervals are the least discussed interval in extant literature. Jensen (2009) attributes this to the difficulty of computation and lack of statistical software packages that readily offer tolerance intervals. De Gryze, Langhans, and Vandebroek (2007) indicated practical guidelines to calculate and use tolerance intervals in real-world applications are currently absent and that for even the simplest regression model, tolerance intervals are lacking.

The relevant interval in some situations in defense testing such as body armor testing should be one that states a specified proportion of population that falls above or below some threshold limit versus merely reporting the mean of the response. Many researchers have conducted studies in the construction of tolerance limits for normal distribution; early works by Wilks (1941, 1942), Wald (1943), and Wald and Wolfowitz (1946) are widely available in the literature. Exact methods for one-sided and two-sided tolerance regions have been researched for the normal distribution. Tolerance intervals for linear regression models were first introduced in the seminal paper by Wallis (1951). Wallis extended the previous work of Wald and Wolfowitz (1946) for a normally distributed sample to a linear regression model. Since then, researchers have extended Wallis's work to multiple and multivariate tolerance intervals (Krishnamoorthy & Mondal, 2008; Lee & Mathew, 2004). The continued research in this field has allowed T&E practitioners to expand their analysis and evaluation to include multiple responses such as time to acquire a target and miss distance. Not discussed in this article are Bayesian methods that incorporate a priori information and are useful in rolling up and including developmental test data and/or subject matter expert opinions. For a review of the statistical tolerance region, including Bayesian tolerance intervals, see Krishnamoorthy and Mathew (2009).

Design of Experiments Framework

A simplified DOE framework (Figure 1) is proposed for use in the DoD T&E community and later applied to the case study. Another suggested framework is the Plan, Design, Execute, Analyze model developed by Eglin Air Force Base, Florida.

FIGURE 1. GENERALIZED DOE FRAMEWORK



Phase 0: Mission Goal Definition

This step is accomplished at the top level and early in the acquisition cycle, where the mission statement and objectives (Critical Operational Issues, or COIs) are clearly defined for the program. COIs answer the question, "What capability will the system provide?" A hierarchy can serve as a catalyst for generating discussion about the identification of factors, levels, and responses for the proposed tests. This is accomplished

2

by the test team—a T&E Working-level Integrated Program Team (WIPT). The T&E WIPT membership should include all stakeholder organizations from the developmental test and operational test communities. Test membership should include, but is not limited to, the program manager, operators, subject matter experts, program analysts, testers, and requirements representative. Generation of goals, objectives, factors, levels, and responses should be an exhaustive process so no input and output variables are left out. Therefore, continuously including these members upfront is critical to improving test outcomes.

Phase 1: Plan and Design

Test goal and objective. Every good experimental design begins with a clear, concise goal and objective that is well understood by all parties before test planning. The right kind of questions leading to development of quantifiable terms (responses) need to be articulated for effective test execution and data collection. The right quantitative metrics are essential for developing a good test design; poorly chosen or ill-defined measures can lead to unnecessary costs or ambiguous test results (Gilmore, 2012b). Continuous metrics, such as detection range, enable the most efficient use of resources and provide the most information. On the other hand, binary metrics, such as pass or fail, hit or miss, offer less information to testers and can increase test resource requirements.

Response variables, factors, and levels. Selection of a response variable, continuous or discrete, should be carefully considered to minimize risk in running into a Type I (α) or Type II (β) error. Responses are Key Performance Parameters, Measures of Effectiveness, Measures of Suitability, Critical Technical Parameters, Key System Attributes, and/or Measures of Performance that are documented and traced to the requirements document (Gilmore, 2012b). In current DoD test planning, the statistical measures of merit—power (1-β) and confidence level (1-α)—must be documented in the Test and Evaluation Master Plan (TEMP; see Gilmore, 2012b). The Type I error (α) is the probability of declaring a factor is affecting the response when in reality it does not. This percent value is typically agreed upon by the decision maker based on inputs from the T&E WIPT. The quantity expresses the decision makers' risk tolerance for making a wrong decision based on limited test data (Freeman, Glaeser, & Rucker, 2011). A Type II error (β) is the probability of declaring a factor does not affect the response, when in reality it does. Power (1-β) is the likelihood of not making the β error and the ability to detect differences. This is set by the test team during test planning. In general, the confidence levels are set between 80% and 95% ($\alpha = 0.20$ to 0.05), and the power for a signal-to-noise S:N = 1.0 should be above 80% (Department of the Army, 2012). Both types of errors must be well understood and explained to the decision maker due to the unintended programmatic consequences that might result from a lack of understanding. Defining factors (independent variables) is no trivial matter and must be determined by the entire test team. The factors define the operational environment of the system. Some proven effective brainstorming methods to aid the process are fishbone diagrams (also known as Ishikawa Diagrams) and process flow diagrams. Note that it is better to include more factors than preclude factors that might be significant (Telford, 2007). Levels are the specified values of the factors, and the general recommendation is to consider two to three levels for each factor (Freeman et al., 2011).

Test design. The test design is constructed after the factor, levels, and responses are identified by the test team. Decision trade-offs between risk and costs are made at this stage with assistance from the test team, especially when test resources are limited. The choice of design involves consideration of sample size, selection of a suitable run order for the trials, and whether blocking or other randomization restrictions exist (Montgomery, 2001). Depending on the test conditions, copious sources of noise might be present and must be considered in the test design. Also, test resources and programmatic constraints may prohibit common designs. Consider the basic principles of DOE when designing a test: randomization, replication, and blocking. Randomization is the underlying foundation of the use of statistical methods. It reduces the likelihood of introducing bias to the experiment by randomizing the effect of uncontrolled variables, such as unplanned weather effects. Replication of test points allows for estimation of system variability and test procedure error. Blocking provides another way to address variability and improves the power to detect a factor effect (Freeman et al., 2011). Coleman and Montgomery (1993) provide guidelines in the preexperimental planning phases to assist with designing and conducting an experiment. Some other papers useful in explaining experimental planning and design include Hunter (1977) and Montgomery (2005).

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Phase 2: Analyze and Build

If all steps leading to this phase are properly and thoroughly planned, then the test is well defined. However, no test execution goes as planned due to nuisance factors and noise that exist such as weather and/or data processing. Data are collected at this phase and analyzed by the test team. A mathematical model is created for each response variable by mapping a response surface over the region of interest (operational range) so that the effect of factors on that response can be studied (Johnson et al., 2012). The analysis will result in generating statistically defensible models that inform the decision maker.

Phase 3: Report

The test team should draw conclusions based on information extracted from test data. Appropriate scientific test and analysis techniques should be employed so that senior leaders can make an informed decision backed by defensible data.

Brief Review of Two-Sided Tolerance Intervals

In this section, two-sided approximation tolerance intervals are considered. To describe a general two-sided tolerance interval form, let x_1, x_2, .., x_n be values of a random sample $X_1, X_2, .., X_n$ of size n from a normal distribution with mean μ and variance σ^2 where:

$$X \sim N(\mu, \sigma^2)$$

The 100(P)% two-sided tolerance interval with confidence 100(1-α)% is of the form $\bar{x} \pm k_2 s$ for which the following applies:

$$Pr[P(\bar{x} - k_2 s < X < \bar{x} + k_2 s) \geq P] = 1 - \alpha$$

where $\bar{x}$ is the sample mean, k_2 is a constant multiplier, s is the sample standard deviation, 1-α is the confidence level associated with the interval, and P is the proportion of distribution covered by the interval, referred to as coverage. To describe the two-sided *regression* tolerance interval, let's consider the general structure for a regression model:

$$y_i = \beta_0 + \beta x_i + \varepsilon_i, i = 1,\ldots,n$$

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where y_i is the *p x 1* response vector, x_i is the known *m x 1* factor variable vector, β_0 is the *p x 1* intercept vector, β is unknown *p x m* regression parameter vector, and ε_i is assumed to be a vector of independent, normally distributed error terms, each with mean zero and variance σ^2. To estimate β, least squares regression is applied based on a set of *n* observations. The predicted mean response would then be of the form:

$$\hat{y} = x\hat{\beta}$$

Suppose for any known value of factors $x = x_i$ with a corresponding fitted value $\hat{y}_i$, the 100(P)% two-sided tolerance interval with confidence 100(1-α)% is of the form:

$$\hat{y}_i \pm k_{2,i}s$$

where k is the tolerance factor and s^2 is the residual mean square error based on degrees of freedom.

Monte Carlo Evaluation of Tolerance Intervals

The first approximation considered was proposed by Howe (1969). Howe introduced an approximate factor for a two-sided tolerance interval for a normally distributed population given as:

$$k_2 = \sqrt{\frac{df(1+\frac{1}{n})z^2_{(1-P)/2}}{x^2_{1-\alpha,df}}}$$

where is $x^2_{1-\alpha,df}$ the αth percentile of the chi-square distribution with *df*, degrees of freedom, *n* is the sample size, $df = n - m$ (number of independent random samples) is degrees of freedom defined as the number of values that are free to vary, and $z_{(1-P)/2}$ is the *p*th percentile of the standard normal distribution.

The second approximation was proposed by Zorn, Gibbons, and Sonzogni (1997). They introduced a weighted tolerance interval for estimating detection and quantification limits in the chemical field. Leveraging the earlier work of Lieberman and Miller (1963) in developing simultaneous tolerance intervals for linear regression, they translated it to a nonsimultaneous case. The two-sided approximation (TI_2) would result in:

$$TI_2 \approx \widehat{y}_0 \pm s\left[t_{\frac{\alpha}{2},df}\sqrt{x_0^T(X^TX)^{-1}} + \Phi^{-1}(P)\sqrt{\frac{df}{\chi^2(1-\frac{\alpha}{2},df)}}\right]$$

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where x_0 is a point in the design space, X is the design matrix of the regression model, $\Phi^{-1}(P)$ is the inverse cumulative normal distribution, and $t_{\frac{\alpha}{2}, df}$ is the Student's t-inverse cumulative distribution function using degrees of freedom for the corresponding confidence.

The third approximation is credited to De Gryze et al. (2007) when they proposed taking α in both χ2 (df) and $t(df)$ quantiles, thus resulting in the approximation below:

$$TI_2 \approx \widehat{y}_0 \pm s\left[t_{\alpha, df}\sqrt{x_0^T (X^T X)^{-1}_{x_0}} + \Phi^{-1}(P)\sqrt{\frac{df}{\chi^2(1-\alpha, df)}}\right]$$

where x_0 is a point in the design space, X is the design matrix of the regression model, $\Phi^{-1}(P)$ is the inverse cumulative normal distribution, and $t_{\frac{\alpha}{2}, df}$) is the Student's t-inverse cumulative distribution function using degrees of freedom for the corresponding confidence.

The final method introduced is the exact two-sided tolerance interval due to Krishnamoorthy and Mathew (2009). The k is the solution of the integral equation:

$$2m\int_0^\infty P\left(1 - F\chi^2_{df}\left(\frac{df}{k^2}\chi^2_{1;P}(d^2z^2)\right)\right)(2\Phi(z)-1)^{m-1}\phi(z) = 1 - \alpha$$

where df is the degrees of freedom, $d^2 = x'(X'X)^{-1}x$ where X is the design matrix of the linear regression model, m is the number of independent random samples (factors), $\Phi(z)$ is the cumulative distribution function, $\phi(z)$ is the probability density function, $F\chi^2_{df}$ is the cumulative distribution function of a chi-square distribution with df degrees of freedom. Detailed derivation of the exact equation can be found in Howe (1969), equations 1.2.3, 1.2.4, 2.5.7, and 2.5.8) and Witkovsky (2013). This article employs the MATLAB tolerance package developed by Witkovsky (2009) using the Gauss-Kronrod quadratic formulae for integration.

The following Monte-Carlo simulation algorithm is applied to approximations by De Gryze et al. (2007), Howe (1969), and Zorn et al. (1997).

1. Simulate 500 design points (x_0) within the test space uniformly distributed throughout the design space.

2. For a given 1-α, p, compute tolerance interval multiplier at x_0 (design point in the test space).

3. Since the tolerance interval multiplier is a function of the position in the design space, take the average tolerance interval multiplier value (based on the Monte Carlo simulation sample of 500 points previously mentioned) and multiply by $t_{\alpha,df}$ to determine the tolerance factor.

Next, the following are computed and compared: (a) the approximate factor by De Gryze et al. (2007), (b) the approximate factor by Zorn et al. (1997), (c) the approximate factor by Howe (1969), and (d) the exact tolerance factor. Figure 2 depicts the comparison case of p = 0.99 and 1-α = {0.90. 0.95, 0.99}.

FIGURE 2. P = 0.99, 1-α = {0.90, 0.95, 0.99}

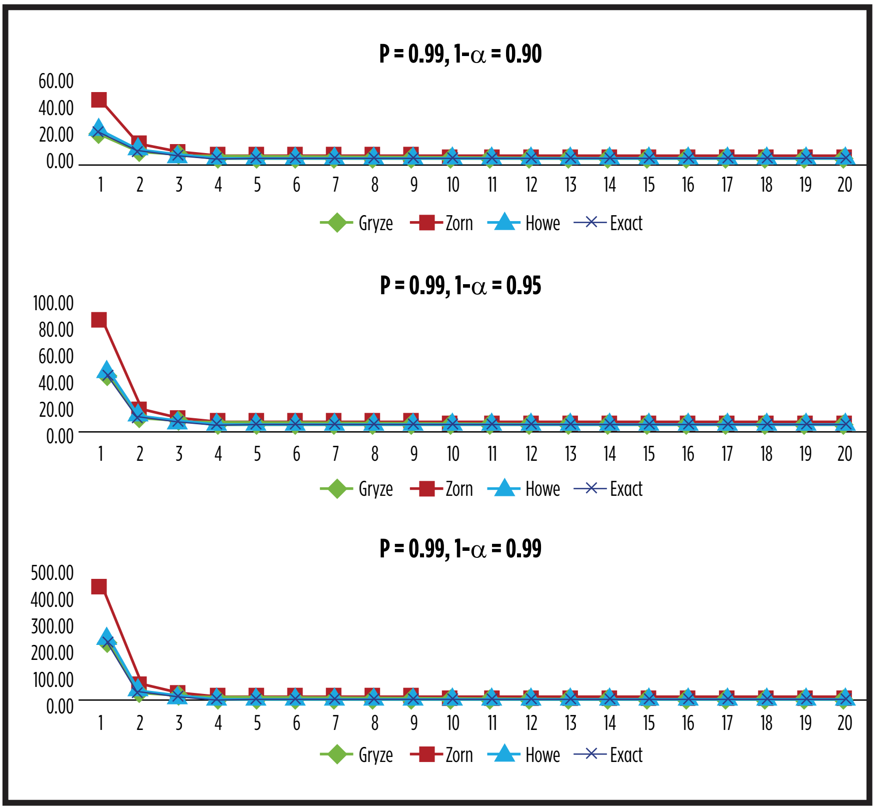

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Figure 2 shows that all tolerance factors decrease as degrees of freedom increase. Immediately apparent is that the Zorn et al. (1997) approximation is the most conservative, especially for smaller degrees of freedom. All numerical results are slightly above the exact method, but the Howe (1969) approximation is slightly lower with larger degrees of freedom. The two-sided tolerance intervals performed well for degrees of freedom 4 and above. The approximated values performed well against the exact method, but it can be noted that Zorn's method would require a larger sample size. In general, to cover a multifactor region requires a wider tolerance region compared to the normal sample. So why investigate approximation methods when an exact method is available? An exact method calculation can be extremely complex and is rarely if ever available on statistical software packages. It can also be thought of as costly, given the difficulty and time involved in obtaining an exact solution. Therefore, approximation methods are generally preferred, but their accuracy is seldom confirmed. If an approximation needs to be used, the author recommends the De Gryze et al. (2007) proposed approximate method as a statistical test analysis method commensurate with designed experiments. The appeal of the De Gryze et al. (2007) method stems from the fact that this method takes into account the design structure and variance, is easier to compute, and is comparable to the exact method.

Use of Tolerance Intervals in Designed Experiment Case Study

This section will apply the two-sided tolerance interval to a designed experiment using a notional case study. The case study used throughout the article is for academic purposes and is by no means representative of any existing weapon employed by the DoD. Some aspects of the case study have been simplified for educational purposes.

Phase 1: Plan and Design

Objective. The objective of the experiment is to characterize the performance of a new and old air-to-ground missile.

Response variables, factors, and levels. Figure 3 and Table 1 show the factors and levels generated by the test team during the test design planning phase. The response variables are miss distance and impact velocity error.

FIGURE 3. FACTORS AND LEVELS GENERATED BY TEST TEAM DURING TEST DESIGN PLANNING PHASE

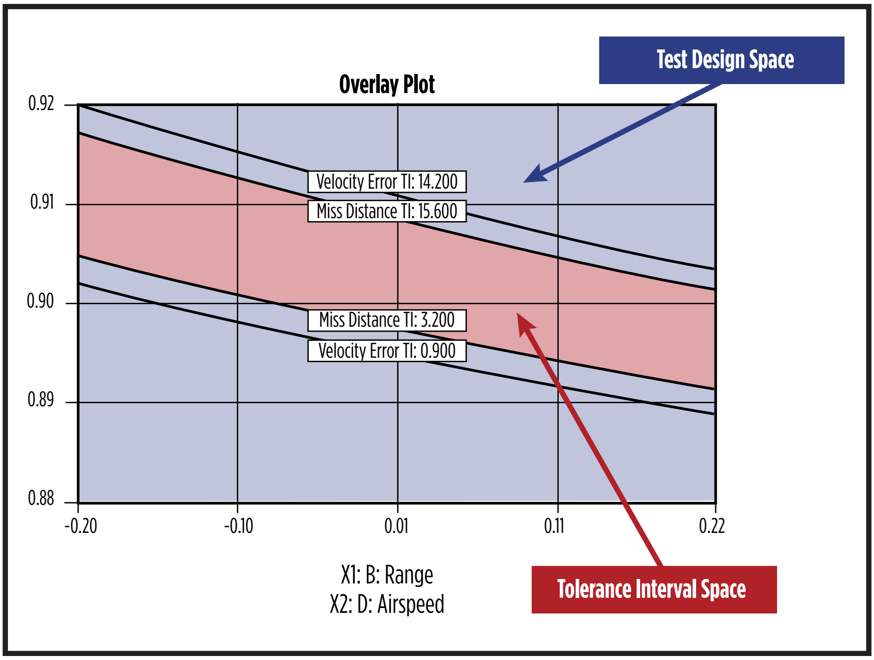

TABLE 1. FACTORS AND LEVELS

	Factor	Levels
A	Variant	0 (Legacy), 1 (New)
B	Range	-1, 1
C	Altitude	25, 35
D	Airspeed	0.85, 0.95

Test design. A 2^4 factorial test design, 16 runs were selected for this case study.

Phase 2: Analyze and Build

Test execution. Suppose the test team executed the test, and Table 2 reflects the results collected.

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Model building. A regression model was built and analyzed. The overall response models were significant; range and airspeed were the two most important factors in characterizing the air-to-ground missile performance, and there was no statistical difference between the legacy and new variant across the operational envelope. However, for this research, analysis will be limited to the tolerance interval computation under high-airspeed and high-range conditions.

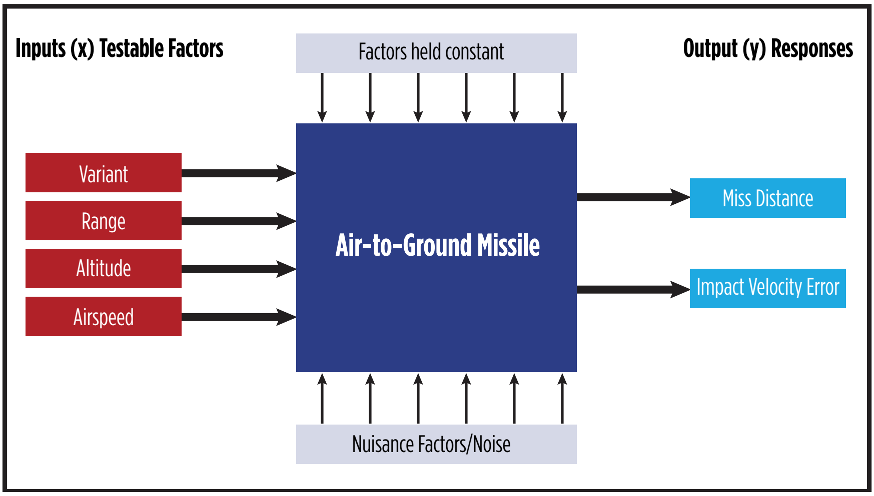
TABLE 2. AIR-TO-GROUND CASE STUDY TEST DESIGN AND RESULTS

Run	A: Variant	B: Range	C: Altitude	D: Airspeed	Miss Distance	Impact Velocity Error
1	1	-1	25	0.95	3.44	1.76
2	0	1	25	0.95	20.09	18.96
3	0	1	35	0.85	5.63	3.4
4	1	-1	35	0.95	8.58	6.71
5	1	-1	35	0.85	1.14	0.76
6	1	1	35	0.95	20.81	18.46
7	0	-1	25	0.85	4.65	2.83
8	1	1	25	0.85	4.45	2.49
9	1	1	25	0.95	19.9	17.51
10	1	1	35	0.85	5.44	3.86
11	0	1	35	0.95	22.47	20.35
12	0	-1	35	0.85	3.55	1.61
13	1	-1	25	0.85	3.04	1.38
14	0	-1	35	0.95	13.76	11.45
15	0	-1	25	0.95	7.58	5.39
16	0	1	25	0.85	5.23	3.7

Phase 3: Report

Based on the models generated, the following values were obtained: mean miss distance response value = 9.36 feet, miss distance standard deviation = 2.33 feet, mean impact velocity error response value = 7.54 feet/s, impact velocity error standard deviation = 2.15 feet/s, and degrees of freedom = 15. Suppose the test team has selected α, confidence = 0.05 (95%) and p, proportion of population = 99%. Referring to the De Gryze et al. (2007) approximation, the test team was able to report "with 95% confidence, at least 99% of the miss distance population will be between 5.0 to 26.3 ft., and at least 99% of the velocity error population will be between 3.9 ft./s to 23.5 ft./s under the specified condition." Now the test team overlaid the two most important factors—range and airspeed—and bounded the "test design space" with tolerance intervals obtained previously for condition 1 (Figure 4). From this plot, the team can easily extract the "sweet spot," "operating window," or in this case the "tolerance interval space" where they can ascertain with a specified confidence that at least 99 percent of both responses would be found, under the specified conditions.

FIGURE 4. RANGE AND AIRSPEED OVERLAY PLOT



Further, the test team investigated how confidence and tolerance intervals compared. The 95 percent confidence interval for miss distance mean and impact velocity error mean were found to be within 13.8 to 17.5 feet, and 12 to 15.4 feet/s, respectively. This means the "true" mean of the miss distance and impact velocity error measurements lies within these bounds. Oftentimes, we might not need to place bounds on the distribution parameters, but on the specified proportion of population instead, hence the appeal of tolerance intervals. The confidence interval may win the interval popular vote; however, the beauty of the tolerance interval lies in the fact it takes into account not only the sample size, but also the estimates of mean and standard deviation noise. Given the test data generated, the test team was able to narrow down and recommend a specific response interval where 99 percent of the population would lie

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at the factors identified under the specified conditions. This enabled the program manager to set an operational window where the air-to-ground missile would perform at its optimum for high airspeeds and high range. (Recall the case study is notional, but this is an illustration of the type of information that can be drawn.)

In this case study, a statistical tolerance interval ensured a defensible conclusion with a sound analytical basis, rather than simply stating the mean as criticized in the DOT&E *FY 2012 Annual Report*. Through the combined use of DOE, regression analysis, and tolerance intervals, T&E practitioners are able to frame the operating window with some confidence and have the ability to map out the test space where factors can be reliably tested. This is a significant improvement over simply stating a single average across all test conditions, and it allows us to extract more information from limited resources and test events. The efficiencies obtained through the meticulous planning using DOE principles were retained. An advanced statistical analysis that complements DOE proved capable of defining an operating window with some certainty and well-understood risks where the air-to-ground missile can be adequately operated. Understanding the appropriate use of statistical analysis technique is imperative and does matter; for example, interaction effects need to be considered and a simple one-way analysis of variance or use of average value might ignore or hide the interaction between main effects. Therefore, the research into suitable advanced statistical analysis methods commensurate with DOE needs to continue.

Through the combined use of DOE, regression analysis, and tolerance intervals, T&E practitioners are able to frame the operating window with some confidence, and have the ability to map out the test space where factors can be reliably tested.

Limitations and Future Research

In general, tolerance intervals offer a better means to assure, with some confidence, that a fixed proportion of the systems' performance over the design space falls within a specified interval. The analysis method reaps the benefits of a designed experiment and employs statistical techniques that are commensurate with DOE. This research, however, does have limitations, indicating a need for further discussion and research. Future research should include qualitative metrics, such as categorical factors. In addition, other tolerance intervals such as nonparametric regression tolerance intervals should be investigated for future use in the defense test community (see Young, 2010, for other intervals). One-sided regression tolerance intervals for defense testing should be presented and compared using the proposed Monte Carlo simulation algorithm; the calculation is generally simpler than the two-sided case. When exact methods are not available, the author recommends using the approximate methods mentioned in this article that are best suited for multiple regression models. Be forewarned that the use of tolerance intervals may require a larger sample size; for this reason and to properly size your experiment, the author also recommends investigating the use of tolerance intervals in test planning (see Whitcomb & Anderson, 2011, for examples).

Recommendations and Conclusions

The defense T&E community has progressed in its efforts to advance statistical rigor within the community over the past 3 years; however, some areas still need improvement. One area is to improve interaction between necessary stakeholder organizations and the T&E community. All organizations that have an impact and/or influence on the program's T&E planning, execution, and assessment need to be engaged in the T&E WIPT as early as possible. Another area would be to increase education and training on the use of STAT for all stakeholders, and this means going above and beyond what confidence intervals provide. Finally, best practices, lessons learned, and research need to be continuously published and readily available to the T&E community.

In these resource-constrained times, every dollar spent on defense must count. As the DoD moves toward generating defensible data through the use of DOE for test designs and institutionalizing statistical rigor

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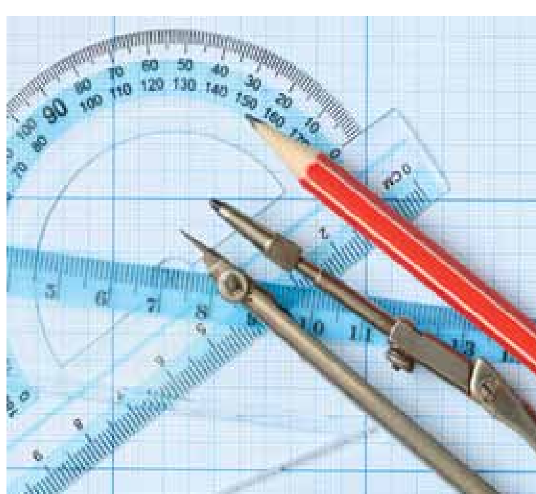
within the T&E community, it seems logical to employ advanced statistical analysis methods that reap the benefits afforded by DOE to generate efficiencies. Rigor should not end with the test design, and solid analytical evidence needs to be presented all the way through test reporting. The literature to date does not adequately address the appropriate use of defensible data developed through improved design methods, nor does it propose a statistical analysis, such as tolerance intervals, commensurate with test designs developed using DOE for the defense community. This article fills that gap by introducing the applicability of tolerance intervals as an analysis technique in a designed experiment and by comparing several two-sided approximate tolerance factors estimated by Monte Carlo simulation to the exact method. Further, this article provides a recommendation of the most appropriate tolerance interval and its applicability to the defense T&E community using a simple case study. This analytical method provides a meaningful objective way to add rigor to an otherwise subjective assessment, extracts more information to state how the system will perform in the operational conditions, and serves as a quantitative decision aid to our senior leaders.



Author Biography

Ms. Alethea Rucker is the chief, Program Integration Branch, Directorate of Space Programs, Office of the Assistant Secretary of the Air Force (Acquisition), Pentagon, Washington, DC. Prior to joining space programs, she was the chief, Intelligence, Surveillance, and Reconnaissance, and Special Operations Forces Programs; and Air Force Scientific Test and Analysis Techniques Implementation Lead for the U.S. Air Force. She holds a BS and MS in aeronautical and astronautical engineering from Purdue University, and is a PhD candidate in systems engineering at The George Washington University.

(E-mail address: alethea.rucker@pentagon.af.mil)

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305

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A Comparative Analysis of the Value of Technology Readiness Assessments

Reginald U. Bailey, Thomas A. Mazzuchi, Shahram Sarkani, and David F. Rico

The U.S. Department of Defense endorsed and later mandated the use of Technology Readiness Assessments (TRAs) and knowledge-based practices in the early 2000s for use as a tool in the management of program acquisition risk. Unfortunately, implementing TRAs can be costly, especially when programs include knowledge-based practices such as prototyping, performance specifications, test plans, and technology maturity plans. What is the economic impact of these TRA practices on the past and present acquisition performance of the U.S. Army, Navy, and Air Force? The conundrum today is that no commonly accepted approach is in use to determine the economic value of TRAs. This article provides a model for the valuation of TRAs in assessing the risk of technical maturity.

« Image designed by Diane Fleischer

Background

The U.S. Government Accountability Office (GAO), formerly the General Accounting Office, has reported on the acquisition performance of major defense acquisition programs (MDAPs) since 1960 (U. S. General Accounting Office, 1988). From the inception of the GAO's mandate to report annually to Congress on its assessment findings, the ability of the U.S. Department of Defense (DoD) to consistently execute its acquisition plan for the purchase of major weapon systems has been erratic, seldom meeting cost, schedule, or original performance objectives. From 1997 to 2012, the DoD's budget grew by almost 200 percent to $529 billion, representing more than 20 percent of the total operating budget of the U.S. government (DoD, 2013b). Amazingly, 31 percent of all MDAPs since 1997 have incurred either a significant or critical Nunn-McCurdy cost breach (DoD, 2013c). In addition, during 1995–2013 each of the military services has experienced cancellation of several major programs without receiving any or very few operational units for the funds expended (DoD, 2013c). Specifically, the Army cancelled 14 MDAPs (Table 1):

TABLE 1. ARMY-CANCELLED MDAPs (1995–2013)

1	Aerial Common Sensor (ACS)	8	Joint Common Missile (JCM)
2	Armed Reconnaissance Helicopter (ARH)	9	Joint Tactical Radio System–Ground Mobile Radio (Army Portion) (JTRS-GMR)
3	Army Tactical Missile System–Brilliant Anti-armor Technology (ATACMS-BAT)	10	Land Warrior Integrated Soldier System
4	C-27J Military Transport Aircraft (Army Portion)	11	Net-Enabled Command Capability (NECC)
5	RAH-66 Comanche Reconnaissance Armed Helicopter	12	Non Line-of-Sight–Land Systems (NLOS-LS)
6	XM2001 Crusader Self-Propelled Howitzer	13	Patriot Medium Extended Air Defense System Combined Aggregate Program Fire Unit (Patriot MEADS CAP Fire Unit)
7	Future Combat System (FCS)	14	Surface Launched Advanced Medium Range Air-to-Air Missile (SLAMRAAM)

The Navy cancelled seven MDAPs (Table 2):

TABLE 2. NAVY-CANCELLED MDAPs (1995–2013)

1	Advanced Deployable System (ADS)	5	Extended Range Munition (ERM)
2	Advanced SEAL Delivery System (ASDS)	6	F-35 Alt Engine (Navy Portion)
3	Expeditionary Fighting Vehicle (EFV)	7	VH-71 Kestrel Presidential Helicopter
4	Electronic Patrol – X (EP-X)		

Finally, the Air Force cancelled 10 MDAPs (Table 3):

TABLE 3. AIR FORCE-CANCELLED MDAPs (1995–2013)

1	Third Generation Infrared System (3GIRS)	6	Expeditionary Combat Support System (ECSS)
2	C-130 Avionics Modernization Program (AMP)	7	F-35 F136 Engine
3	C-27J Joint Cargo Aircraft	8	National Polar-Orbiting Operational Environmental Satellite System (NPOESS)
4	Combat Search and Rescue (CSAR-X)	9	Space Based Space Surveillance (SBSS) Follow-on
5	E-10 Multi-Sensor Command and Control Aircraft (E-10 MC2A)	10	Transformational Satellite Communications System (TSAT)

In 1999 the U.S. General Accounting Office defined a framework of acquisition practices modeled after commercial best practices that emphasized knowledge-based decision making, and recommended its adoption by the DoD (U.S. General Accounting Office, 1999). The DoD adopted knowledge-based practices in 2001 with the issuance of DoD Directive (DoDD) 5000.1 and DoD Instruction (DoDI) 5000.2 (see DoD 2013e; 2013a, respectively). Starting in May 2003, and annually thereafter, the GAO has reported to Congress its assessment of the acquisition performance of MDAPs, emphasizing the DoD's use of mature technologies Technology Readiness Assessments (TRAs). Such assessment includes adherence to knowledge-based acquisition practices such as prototyping, performance specifications, test plans, and technology

3

maturity plans (U. S. General Accountability Office, 2005, 2006, 2007, 2008a, 2009, 2010, 2011, 2012; U. S. General Accounting Office, 2003, 2004). The DoD attributes a significant proportion of poor acquisition performance to the incorporation of immature technologies into its weapon system acquisitions by DoD components, Defense agencies, and their suppliers. Associated with the DoD's yearly multibillion dollar budget for the procurement of military weapon systems is the expenditure of millions of dollars each year performing TRAs as one of the approaches to monitor and control the perceived risk of incorporating immature technology into the acquisition process. The DoD uses TRAs as a means of identifying key components, referred to as critical technologies (CT), and assessing their maturity using a nine-point Technology Readiness Level (TRL) scale (Mankins, 1995). As part of a TRA, an independent team of subject matter experts assists the program manager (PM) in the process of identifying CTs believed to be the major drivers of cost and schedule performance during the acquisition. The team also assists the PM in assessing component maturity and assigning TRLs. Their assessment is then documented in a TRA report prior to the major decision-making juncture in the overall acquisition life cycle (i.e., Milestone B). (Note that the TRA report is mandated by the Milestone Decision Authority [DoD, 2011a, 2011b].) Typically CTs are advanced or leading-edge technology that will push the performance envelope of the weapon system, thus providing a strategic military advantage (Petraeus, 2010). The DoD believes that identifying and mitigating the use of immature technologies (i.e., TRL < 6) early is the key to improving overall acquisition performance (i.e., reducing cost and schedule overruns, increasing delivery order quantities, successful weapon systems deployment, etc.)

(Cancian, 2010; DoD, 2009; U. S. General Accounting Office, 1998, 1999). Bailey, Mazzuchi, Sarkani, and Rico (2014) reported, however, that during 2003–2012 only slightly more than half—58.1 percent—of the CTs being used in development acquisitions were sufficiently matured (i.e., TRL ≥ 6) (see Table 4). This tendency to proceed into development or production with less knowledge than required has led to similar results experienced over the last five decades, with several programs failing to meet the original cost, schedule, and performance objectives (Bair, 1994; Fox, 2011; U. S. General Accounting Office, 1988).

3

TABLE 4. 2003–2012 DoD CT MATURITY ASSESSMENTS

Year	Critical Technologies		
	Immature	Total	Mature
2012	103	345	70.1%
2011	106	371	71.4%
2010	105	372	71.8%
2009	177	420	57.9%
2008	208	466	55.4%
2007	241	451	46.6%
2006	225	428	47.4%
2005	251	443	43.3%
2004	193	391	50.6%
2003	39	117	66.7%
Avg	**165**	**380**	**58.1%**

Sources: U.S. General Accounting Office, 2003, 2004; GAO 2005, 2006, 2007, 2008a, 2009, 2010, 2011, 2012

Utilization of proven technologies that offer moderate performance improvements, yet are well understood in terms of meeting scope, cost, schedule, and performance constraints, is DoD's preferred acquisition approach. Currently, however, basic arguments favor applying the five-stage DoD acquisition life cycle defined by DoD (2013d). This life cycle includes up-front investments in large-scale system prototypes during the Technology Demonstration (TD) phase; and the performance of TRAs, along with identifying their associated CTs, assigning TRLs, and ensuring they reach sufficient maturity—all are qualitative at best and are based only on engineering judgment or face validity. Clausing and Holmes (2010) devised a structured technology readiness method that added quantification measures in an attempt to remove perceived subjectivity within the National Aeronautics and Space Administration's TRL framework. However, little quantitative evidence has been collected on the actual economic benefits of technology maturity via TRAs for any of the military Services. Therefore, the purpose of this article is to examine the wealth of information emerging from government agencies such as the GAO, DoD, and others and apply economic models to begin examining the quantitative benefits of technology maturity for the major programs of each of the military Services. The results of this analysis should help members of the acquisition community determine whether TRA knowledge-based practices have a positive effect on acquisition outcomes. More important, in today's environment of fiscally austere federal budgets and after the impact of the sequester, such evidence may also be of benefit to military strategists if the use of TRAs helps reduce cost and schedule overruns and increases delivery order quantities (DoQs) for the Army, Navy, and Air Force (Petraeus, 2010).

Utilization of proven technologies that offer moderate performance improvements, yet are well understood in terms of meeting scope, cost, schedule, and performance constraints, is DoD's preferred acquisition approach.

Problem

The DoD portfolio of MDAPs currently stands at 95, for fiscal year 2013, with an estimated cost for development and procurement of nearly $1.7 trillion (DoD, 2013b). Overall acquisition performance has been less than stellar, and a significant proportion of the programs suffer from excessive cost, schedule overruns, and dramatically reduced DoQs, while some have been cancelled outright. The DoD's position is that technology maturity, or lack thereof, is a primary measure of acquisition performance (GAO, 2008b). That is, weapon systems that use mature technologies will have better acquisition performance than those using immature technologies (Weapon Systems Acquisition Reform Act, 2009). Technical maturity (or knowledge-based practices as they are frequently called) such as the TD phase, full-scale system prototype, and the TRA process together may cost up to 10 percent of the acquisition budget through the manufacturing phase. The fundamental concept is that these up-front technology maturity investments will head off downstream manufacturing, operating, and maintenance costs (Assessment Panel, 2006; DoD, 2008; Olagbemiro, Mun, & Shing, 2011). Each of the military Services has incurred costs implementing the TRA process as mandated by the DoD and have assumed the advertised benefits would lead to a successful acquisition. However, little data are available on the economic benefits of performing TRAs. Even the most avid supporters of TRAs want to quantify their economic benefits (Dubos, Saleh, & Braun, 2008; Kenley & El-Khoury, 2012). The use of economic valuation is experiencing a revival of sorts throughout the project management, engineering, information technology, and acquisition communities (Honour, 2004; Reinertsen, 2009). Among these, the most commonly cited measure of business value is the concept of return on investment or ROI (Morgan, 2005). That is, cumulative economic benefits less costs, divided by costs. Today, however, economists promote a suite of other, more valid measures, such as net present value (NPV), internal rate of return, real options analysis (ROA), and numerous other measures of project performance (Tockey, 2004). The majority of these methods are what is known as top-down parametric models, which require only a few basic inputs such as costs, benefits, interest rate, time horizon, or even risk. Costs and benefits are the key inputs. Cost data are being collected with increasing frequency, and soft, nonquantifiable benefits are sometimes collected as well. It's only when the latter are converted into economic terms, or monetized, that the portfolio of economic equations and models may be applied. In spite of the myriad complex economic methods, three basic forms seem to be standing the test of time (i.e., ROI, NPV, and ROA). Therefore, the basic research problem or question, given the DoD mandate requiring TRAs for all MDAPs, is this: What are the economic benefits of applying TRAs for each military Service? More specifically, what is the associated cost, benefit, ROI, NPV, and ROA of TRAs? Consequently, the fundamental goal and objective of this article is to collect and analyze MDAP acquisition data, apply some of these basic economic models, and explore the economic value of applying TRAs to acquisitions of each military Service.

3

Research Method

The research method developed for this article involved collecting measurements, which were used to analyze the value of TRAs for each military Service. It was used to help determine the costs and benefits of technology maturity and whether it translates to improved acquisition performance. First, a spreadsheet model was constructed consisting of basic attributes, such as government agency, program type, program name, acquisition costs, and technology maturity. Then other fundamental valuation drivers were added to derive key indicators of value, such as acquisition risks, TRA costs, and TRA benefits. Using the basic acquisition attributes and derived data, metrics and models were then added to help determine the value of TRAs. These included benefit/cost ratio (B/CR), ROI, NPV, breakeven point (BEP), and ROA. The cost-and-benefit spreadsheet was then populated with acquisition data from GAO reports of the major programs from each military Service covering a 10-year period—2003 to 2012—for further analysis. These seven metrics were originally outlined by Rico (2007) as follows:

1. Costs = Total amount of money spent on technology readiness
2. Benefits = Total amount of money gained from technology readiness
3. B/CR = Ratio of technology readiness benefits to costs
4. ROI percent = Ratio of adjusted technology readiness benefits to costs
5. NPV = Discounted cash flows of technology readiness
6. BEP = Point when benefits exceed costs of technology readiness
7. ROA = Business value realized from strategic delay due to risk

ROA attempts to estimate the value of the flexibility a PM has to change direction of a project as new data and information emerge to help remove uncertainty about the viability of a chosen or desired path (de Weck, de Neufville, & Chaize, 2004). Trigeorgis (1993) asserted that managerial flexibility is a set of real options that may consist of options to defer, abandon, contract, expand, or switch investment. Each of these options may result in a different valuation. The Black-Scholes method for determining real option value was chosen for this study as it provides the most accurate valuation available today. As suggested earlier, parametric forms of ROA have emerged making it possible to analyze acquisition performance (Black & Scholes, 1973; Kodukula & Papudesu, 2006).

Data Analysis and Results

3

A recent report by the GAO provided detailed cost data of 47 DoD programs from the 2012 MDAP portfolio, which is the first required input for determining the ROI of TRAs (GAO, 2012). Risk is the second required input for determining ROI of TRAs. Management of risk is a key element in the operational planning of any major system development. Identifying and quantifying the technological risk of a program may have been challenging in the past; however, the GAO report on the 2012 MDAP portfolio provided the necessary information for estimating risks: (a) total cost, and (b) technology maturity (GAO, 2012). Technology maturity is the ratio of immature to total critical technologies (equally weighted), which allows us to determine technology risk as the normalized rank of technology maturity. Cost risk is the normalized rank of total costs, which when combined with technology risk gives a combined risk. Finally, we determine an overall risk percentage as the normalized combined risk. Armed with these measures, we are able to unlock the benefits of technology stability and maturity, and reveal the third input—the economic benefits of performing TRAs. The GAO report on 2012 MDAPs provided three data points for determining the benefits of TRAs: (a) total costs, (b) technology maturity, and (c) the average cost savings from technology stability and maturity. Benefits are a product of total costs, risk, and an average reported benefit of 29.7 percent (GAO, 2007). Based on a sensitivity analysis, benefits were moderated and smoothed by the normalized costs. The following discussion utilizes these measures in analyzing the value of TRAs for each military Service.

Value Analysis of TRAs for Army, Navy, and Air Force MDAPs

A multitude of economic equations–such as cost, benefit, B/CR, ROI percent, NPV, BEP, and ROA–many of which were first introduced during the industrial revolution, help determine the business value of an investment such as cost, benefit, B/CR, ROI percent, NPV, BEP, and

3

ROA (Rico, 2007). ROI percent, which is a ratio of benefits to costs less the costs, is one of the oldest measures used to estimate business value (Phillips, 1997). Although having some similarity with ROI percent, NPV additionally takes into account the time-value of money (e.g., devaluation due to inflation) and is considered more realistic and economically responsible. During the 1970s, ROA emerged as a measurement approach to estimate the value of investments as a strategy of delaying investments due to risk presence (Black & Scholes, 1973; Kodukula & Papudesu, 2006). Rico (2007) posits that ROI percent is used for determining near-term benefits, NPV for mid-term benefits, and ROA for longer term benefits in the presence of risk. Our study utilizes all three vantage points in analyzing the acquisition data for the Army, Navy, and Air Force: (a) ROI percent, (b) NPV, and (c) ROA (see Tables 5–7, respectively).

TABLE 5. ILLUSTRATIVE ARMY ROI DATA FROM 2012 MDAP PORTFOLIO

No.	Program	Cost	Benefit	B/CR	ROI%	NPV	Breakeven	ROA
17	Excalibur	$178.1	$472.5	2.7:1	165.4%	$231.1	3.9 Years	$333.8
28	JHSV	$367.4	$851.5	2.3:1	131.7%	$369.9	5 Years	$567.6
23	Gray Eagle	$515.9	$983.3	1.9:1	90.6%	$335.5	7.7 Years	$624.8
4	IAMD	$552.9	$963	1.7:1	74.2%	$280.9	9.8 Years	$608.2
31	JTRS AMF	$816.1	$1,039.9	1.3:1	27.4%	$84.4	48.4 Years	$660.8
32	JTRS HMS	$835.8	$1,035.8	1.2:1	23.9%	$61.1	68.4 Years	$658.8
3	AH-64D Block IIIa	$1,073.7	$1,141.4	1.1:1	6.3%	-$85.3	-62.9 Years	$729.7

Note. All costs and benefits are in millions of dollars. IAMD = Integrated Air and Missile Defense; JHSV = Joint High Speed Vessel; JTRS AMF = Joint Tactical Radio System Airborne & Maritime/Fixed Station; JTRS HMS = Joint Tactical Radio System Handheld, Manpack, and Small Form Fit.
Source: GAO, 2012

TABLE 6. ILLUSTRATIVE NAVY ROI DATA FROM 2012 MDAP PORTFOLIO

No.	Program	Cost	Benefit	B/CR	ROI%	NPV	Breakeven	ROA
25	IDECM	$82.2	$239	2.9:1	190.9%	$124.8	3.3 Years	$175
38	NMT	$188.1	$532.2	2.8:1	183.0%	$272.7	3.4 Years	$385.7
45	VTUAV	$261.5	$725.7	2.8:1	177.5%	$366.9	3.6 Years	$522
41	SSC	$441.3	$1,165.3	2.6:1	164.1%	$567.8	3.9 Years	$821.7
37	MUOS	$697.8	$1,709.2	2.4:1	144.9%	$782.2	4.5 Years	$1,166.3
11	BAMS	$1,305.2	$2,605.4	2.0:1	99.6%	$950.8	6.9 Years	$1,666
16	E-2D AHE	$1,774.7	$2,920.8	1.6:1	64.6%	$754.4	11.8 Years	$1,843.1

Note. All costs and benefits are in millions of dollars. BAMS = Broad Area Maritime Surveillance; E-2D AHE = Advanced Hawkeye; IDECM = Integrated Defensive Electronic Countermeasures; MUOS = Mobile User Objective System; NMT = Navy Multiband Terminal; ROA = Real Options Analysis; ROI = Return on Investment; SSC = Ship-to-Shore; VTUAV = Vertical Take-Off and Landing Tactical Unmanned Aerial Vehicle.
Source: GAO, 2012

TABLE 7. ILLUSTRATIVE AIR FORCE ROI DATA FROM 2012 MDAP PORTFOLIO

No.	Program	Cost	Benefit	B/CR	ROI%	NPV	Breakeven	ROA
27	JASSM-ER	$373	$1,097	2.9:1	194.1%	$576.9	3.2 Years	$806.5
21	GPS III	$421.1	$1,236.7	2.9:1	193.7%	$649.8	3.2 Years	$908.8
19	FAB-T	$468.8	$1,375.3	2.9:1	193.3%	$722	3.2 Years	$1,010.2
12	C-130 AMP	$620.4	$1,812.7	2.9:1	192.2%	$949.2	3.3 Years	$1,329.5
40	MQ-9	$1,191.9	$3,429.1	2.9:1	187.7%	$1,777.4	3.4 Years	$2,500.9
43	SBIRS High	$1,826.7	$5,165.1	2.8:1	182.8%	$2,645.7	3.5 Years	$3,742.5
33	KC-46	$4,412.7	$10,464.4	2.4:1	137.1%	$4,648.3	4.7 Years	$7,041.1

Note. All costs and benefits are in millions of dollars. C-130 AMP = C-130 Avionics Modernization Program; FAB-T = Family of Advanced Beyond-Line-of-Site Terminals; GPS III = Global Positioning System III; JASSM-ER = Joint Air-to-Surface standoff Missile-Extended Range; KC-46 = KC-46 Pegasus Military Aerial Refueling and Strategic Transport Aircraft; MQ-9 = MQ-9 Reaper Unmanned Aerial Vehicle; ROA = Real Options Analysis; ROI = Return on Investment; SBIRS High = Space-Based Infrared System High.
Source: GAO, 2012

3

We examined the model results for each of the military Service portfolios. The Army's acquisition performance, as reported in its 2012 portfolio of MDAPs, exhibited a wide range of performance. For example, the B/CR performance estimate ranged from 1.1:1 to 2.7:1, and the BEP from -62.9 years to 3.9 years. Conversely, the Navy's B/CR ranged from 1.6:1 to 2.9:1, and the BEP from 11.8 years to 3.3 years, while the Air Force's B/CR ranged from 2.4:1 to 2.9:1, and the BEP from 4.7 years to 3.2 years. This performance may indicate a lack of consistent institutional adherence to DoDI 5000.02 by the Army, although further detailed analysis is required. The Navy's acquisition performance, as reported in its 2012 portfolio of MDAPs, appears to exhibit more consistency within its portfolio of programs in reaping the benefits of TRA knowledge-based practices than the Army. In particular, a higher percentage of its programs had an ROI greater than 100 percent, which may indicate a more effective CT selection process that leverages sufficiently matured technology for incorporation into development programs, although less than that accomplished by the Air Force. The Air Force's acquisition performance, as reported in its 2012 portfolio of MDAPs, appears to exhibit even more consistency within its portfolio of programs in reaping the benefits of TRA knowledge-based practices than the Army or Navy. Of particular note is that a higher percentage of the Air Force programs had a B/CR measurement of 2.8:1 or higher; additionally, the Service reached its BEP sooner (< 3.5 years). This performance may indicate a greater efficiency in program acquisition and operation due to greater adherence to knowledge-based practices.

A sampling of the case study analysis performed for each portfolio is provided in the following discussion. Each case provides additional insight into the potential economic risk associated either with or without sufficiently mature critical technology.

Analysis of AH-64D Block IIIa. The Army's Apache Block IIIa program (AB3A) is an upgrade of the "AH-64D Longbow helicopters to improve performance, situational awareness, lethality, survivability, and interoperability, and to prevent friendly fire incidents" (GAO, 2012, p. 45). The program acquisition state for this study was in the early stages of the Production and Deployment (P&D) phase. Upon determination of costs and benefit of TRAs for the AH-64D Block IIIa, our model estimates values for the other five metrics (i.e., B/CR, ROI percent, NPV, BEP, and ROA). Our analysis of the B/CR metric reflects a less-than-favorable valuation. It indicates, for every dollar expended, only a relatively small percent (i.e., 10 percent) is returned as benefit. The ROI percent valuation, which also reflects a simple cost-benefit ratio, less the costs, without consideration for the time value of money, shows only a 6.3 percent return on the program's investment in TRA practices, or $.063 saved for every dollar invested. The NPV valuation incorporates the time value of money in the economic evaluation and provides the present value of the estimated return. In a traditional business decision-making scenario, a positive difference between NPV and cost provides justification to proceed with the program or investment. The NPV valuation here reflects a significant negative valuation of -$85.3 million, and may provide sufficient justification to halt the program or investment. The BEP valuation reflects being unable to recoup the full initial cost of investment in TRA practices due to the remaining immaturity of critical technologies and unstable requirements. Finally, the ROA valuation results in an estimated return of $729.7 million, which is $674.4 million more than the NPV estimate, and is an estimated $344.7 million less than the cost of implementing TRA practices. In this example of the AB3A program, several of the key ROI metrics suggest an unstable technology base and cost risk, and that the program risk in proceeding into the next phase is high.

Analysis of Mobile User Objective System (MUOS). The Navy's MUOS is "a satellite communications system that is expected to provide a worldwide, multi-Service population of mobile and fixed-site terminal users with increased narrowband communications capacity and improved availability for small terminal users" (GAO, 2012, p. 111). The program acquisition state for this study was in the early stages of

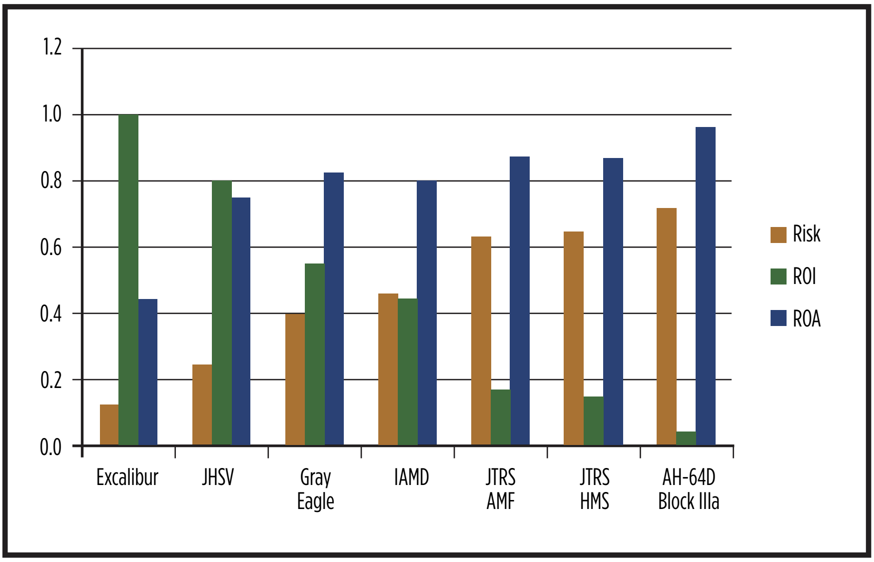
the P&D phase. The B/CR valuation reflects an impressive value added between the cost of implementing TRA and knowledge-based practices, and the potentially derived benefits. About $2.40 of benefit is gained or saved for every dollar expended (i.e., efficiency). The ROI percent valuation indicates an approximate return of 144.9 percent on the program's investment in TRA practices, or approximately $1.44 saved for every dollar invested. The NPV valuation result is approximately $782.2 million. The BEP valuation reflects being able to recoup (in efficiency gains) the full initial cost of the investment in TRA practices in approximately 4.5 years. Finally, the ROA valuation results in an estimated return of $1,166.3 million, which is $384.1 million more value than the NPV estimate, and an estimated return of $468.5 million above the cost of implementing TRA practices. In this example of the MUOS program, all of the key ROI metrics suggest a sufficiently mature technology base. Furthermore, it indicates the technological risk of proceeding into the next development phase is low.

Analysis of JASSM-ER. The Air Force's Joint Air-to-Surface Standoff Missile–Extended Range (JASSM-ER) program will "field a next-generation cruise missile capable of destroying the enemy's war-sustaining capability from outside its air defenses. The JASSM-ER missiles are low-observable, subsonic, and have a range greater than 500 miles" (GAO, 2012, p. 91). The program acquisition state for this study was in the early stages of the P&D phase. Similar to the MUOS program, the resultant economic valuations are equally impressive. Of particular note here, the ROA valuation results in an estimated return of $806.5 million, which is $229.6 million more value than the NPV estimate, and an estimated return of $432.9 million above the cost of implementing TRA practices. Similar to the MUOS program, all of the JASSM-ER program key ROI metrics suggest a sufficiently mature technology base. It also indicates the technological risk of proceeding into the next development phase is low.

Summary of Data Analysis

Using our model, the data from the GAO (2012) report on the 2012 MDAP portfolio were first sorted by risk percent in ascending order. The data were then filtered by military Service. Figures 1, 2, and 3 provide illustrative histograms of each of the Services' programs that have been highlighted in this article. The first major finding revealed by this analysis, and consistent across the portfolios of the military Services, was that ROI percent decreases as program risk and cost increase. This coincides with results from other studies: larger programs are inherently more complex and risk-prone than smaller, shorter duration programs, which have exhibited as much as a 90 percent success rate (Benediktsson & Dalcher, 2005). In addition, increasing risk percent indicates decreasing technology maturity; consequently, programs with a larger number of unstable and immature technologies will have a larger risk and lower ROI. The most significant finding is that ROA increases as risk increases and ROI percent decreases, especially if risk-reducing acquisition practices are used, such as evolutionary acquisition, dividing acquisitions into smaller increments, and spiral development (Benediktsson & Dalcher, 2005; Reagan & Rico, 2010). Delaying a program due to size and technology instability and immaturity by dividing the scope into numerous smaller increments, spirals, and iterations across the entire acquisition life cycle may result in greater economic benefits for each military Service. This supports the concept provided by other studies, which reflect that when there is heightened risk, the flexibility to delay a decision or investment can be quite valuable (Dixit & Pindyck, 1995; Fichman, Keil, & Tiwana, 2005; Luehrman, 1995; Trigeorgis, 1993).

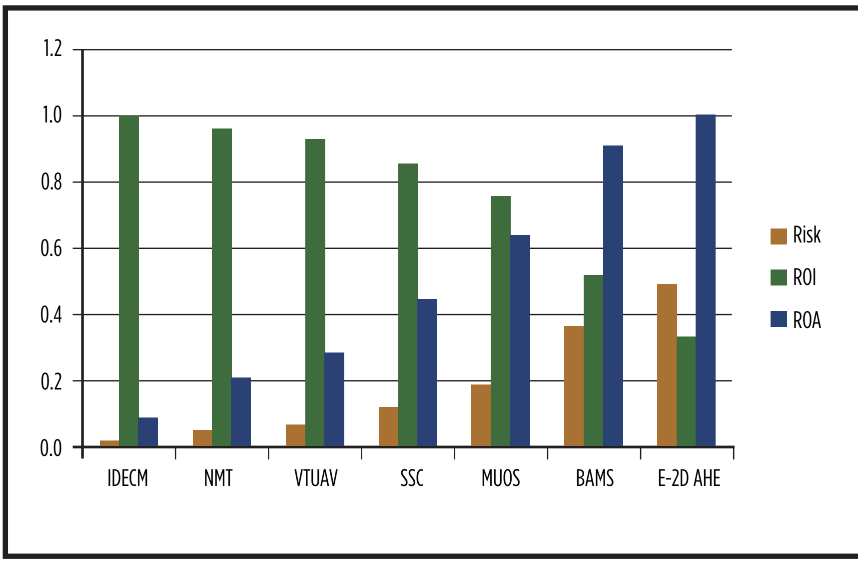
FIGURE 1. ILLUSTRATIVE ARMY RISK, ROI, AND ROA DATA FROM 2012 MDAP PORTFOLIO



Source: GAO, 2012

It can be seen from the earlier examples that the use of classical economic valuation methods may provide useful management insight into the state of an acquisition program. In addition, ROA may provide each military Service a useful estimate of the value of deferring a program until its technologies are sufficiently mature, even when NPV indicates no further investment may be warranted, hence our motivation for including ROA in our process framework (Kodukula & Papudesu, 2006).

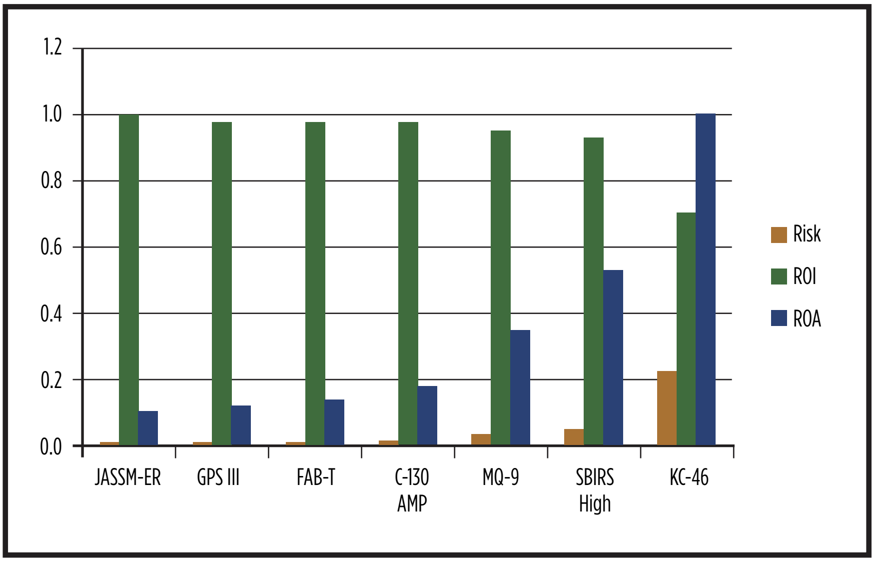
FIGURE 2. ILLUSTRATIVE NAVY RISK, ROI, AND ROA DATA FROM 2012 MDAP PORTFOLIO



Source: GAO, 2012

Delaying a program due to size and technology instability and immaturity by dividing the scope into numerous smaller increments, spirals, and iterations across the entire acquisition life cycle may result in greater economic benefits for each of the military services.

FIGURE 3. ILLUSTRATIVE AIR FORCE RISK, ROI, AND ROA DATA FROM 2012 MDAP PORTFOLIO



Source: GAO, 2012

Trend Analysis (2003–2012)

As we extended our study of the GAO data to encompass the 2003–2012 period, our analysis indicated what appears to be inconsistency in the level of adherence and commitment by the individual military Services in their execution of knowledge-based acquisition practices mandated by Congress and the DoD (U. S. General Accounting Office, 2003, 2004; GAO, 2005, 2006, 2007, 2008a, 2009, 2010, 2011, 2012). Specifically, as reflected in Table 8, we found, on average, taht 40 percent of the Army's MDAP CTs rated as sufficiently mature, compared to 57 percent for the Navy and 67 percent for the Air Force. Perhaps even more telling is that the commitment level of adherence to TRA knowledge-based practices appears to have carried through to the level of acquisition performance success realized during this decade. This seems to be consistent with results from other studies by the GAO and DoD, showing that technology maturity, or lack thereof, is a predictor of acquisition performance (DoD, 2008; GAO, 2008b). Moreover, weapon systems that use mature technologies will have better acquisition performance than those using immature technologies.

3

TABLE 8. 2003–2012 DoD MILITARY SERVICES CT MATURITY ASSESSMENTS

Year	Army Critical Technologies			Navy Critical Tehnologies			Air Force Critical Technologies		
	Immature	Total	Mature	Immature	Total	Mature	Immature	Total	Mature
2012	35	83	57.8%	34	109	68.8%	25	74	66.2%
2011	44	122	63.9%	31	102	69.6%	29	82	64.6%
2010	43	106	59.4%	35	104	66.3%	8	72	88.9%
2009	83	124	33.1%	40	100	60%	18	82	78%
2008	81	128	36.7%	48	117	59%	30	96	68.8%
2007	91	125	27.2%	71	160	55.6%	44	108	59.3%
2006	99	140	29.3%	63	103	38.8%	44	98	55.1%
2005	104	118	11.9%	76	130	41.5%	47	105	55.2%
2004	85	109	22%	60	102	41.2%	30	102	70.6%
2003	7	19	63.2%	10	33	69.7%	11	37	70.3%
Avg	**67**	**107**	**40.451%**	**47**	**106**	**57.061%**	**29**	**86**	**67.7%**

Source: U.S. General Accounting Office, 2003, 2004; GAO, 2005, 2006, 2007, 2008a, 2009, 2010, 2011, 2012

For each of the military Services, and the DoD overall—including the Marines and Missile Defense Agency—a few trends seemingly emerge as reflected in Table 9: (a) an overall lowering of risk percent in the weapon system portfolio, which indicates an overall reduction in the incorporation of immature technology into development programs; (b) an overall improvement in B/CR, indicating growth in execution efficiency; (c) overall growth in ROI percent, indicating a trend of maximizing return on technology choices; (d) improvement in BEP, indicating less time needed before the benefits of technology readiness exceed costs; and (e) an overall lowering of ROA valuation as risk percent is lowered, indicating more programs are waiting for critical technologies to mature before entering into development. The trends seem to suggest that the incorporation of TRAs and knowledge-based practices into the acquisition programs of each military Service may indeed improve cost, schedule, and technical performance of those programs, and consequently of the overall DoD weapon systems portfolio.

TABLE 9. SUMMARY ROI OF TRA ANALYSIS OF U.S. GAO MDAP DATA FROM 2003–2012

Yr.	No. Pgms	Critical Technologies			Risk %	Cost	Benefit	B/CR	ROI	NPV	BEP (Yrs)	ROA
		Immature	Tot	Mature								
2012	47	103	345	70.1%	8.0%	$82,935.8	$228,547.6	2.8:1	175.6%	$114,962.5	3.6	$163,957.1
2011	49	106	371	71.4%	8.7%	$83,456.8	$228,483.7	2.7:1	173.8%	$114,386.1	3.6	$163,487.4
2010	55	105	372	71.8%	9.6%	$87,909.6	$238,416.2	2.7:1	171.2%	$118,533.9	3.7	$169,952.1
2009	59	177	420	57.9%	10.2%	$97,444.3	$262,715.5	2.7:1	169.6%	$130,039.9	3.7	$186,825.9
2008	72	208	466	55.4%	8.7%	$106,304.8	$291,048.4	2.7:1	173.8%	$145,712.6	3.6	$208,258.1
2007	62	241	451	46.6%	10.0%	$87,997.8	$237,794.1	2.7:1	170.2%	$117,907.0	3.7	$169,261.4
2006	51	225	428	47.4%	11.2%	$84,425.8	$225,533.7	2.7:1	167.1%	$110,862.8	3.8	$159,782.8
2005	54	251	443	43.3%	11.3%	$80,422.3	$214,634.1	2.7:1	166.9%	$105,428.4	3.8	$152,001.2
2004	51	193	391	50.6%	10.9%	$67,429.3	$180,664.2	2.7:1	167.9%	$89,007.0	3.8	$128,150.2
2003	26	39	117	66.7%	12.0%	$47,702.0	$126,332.6	2.6:1	164.8%	$61,688.8	3.9	$89,182.2

Note. All costs and benefits are in millions of dollars.
Source: U.S. General Accounting Office, 2003, 2004; GAO, 2005, 2006, 2007, 2008a, 2009, 2010, 2011, 2012

Conclusions

For several decades the DoD and Congress have endeavored to institute, revamp, refine, tweak, overhaul, and reform the Defense Acquisition System in attempts to structure a system of procuring major weapon systems as efficiently, effectively, and affordably as possible, but unfortunately, without achieving significant sustained improvement (Bair, 1994; DoD, 2013b; Fox, 2011; U. S. General Accounting Office, 1988). Acquisition performance continues to struggle and manifest itself in the form of cost and schedule overages, and reduced DoQs. Economic evidence, however, is starting to emerge indicating that investments in knowledge-based practices, especially TRAs as a means of achieving technology maturity, are beginning to pay off. In this article, we have introduced a model to evaluate the costs and benefits of the current MDAP portfolios of the U.S. Army, Navy, and Air Force using classic economic techniques such as ROI, NPV, and ROA. We have shown there is added ROI valuation due to the use of TRAs for MDAPs. We have also shown that the ability to delay a decision to move into development/production until CTs (and associated risk) are sufficiently matured (mitigated) may provide significant cost benefit to a program. We have defined a set of valuation metrics for ROI of TRAs that includes costs, benefits, B/CR, ROI percent, NPV, BEP, and ROA. Indeed, used along with traditional discounted cash-flow methods, real options analysis provides additional insight for the decision maker into the cost and technology risk for MDAPs. In addition, use of the TRA framework enhances opportunities to maximize ROI from new, complex technologies targeted for MDAPs. The ROA measure supports (a) valuation of the decision to delay, (b) identification and quantification of risk associated with CTs, and (c) prioritization of program development and mitigation of risks.

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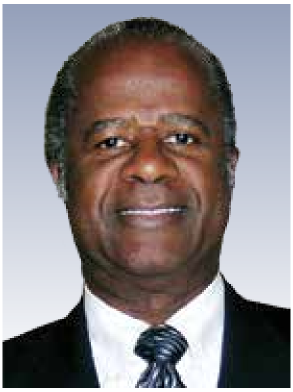
Acquisition performance continues to struggle and manifest itself in the form of cost and schedule overages and reduced DoQs. Economic evidence, however, is starting to emerge indicating that investments in knowledge-based practices, especially TRAs as a means of achieving technology maturity, are beginning to pay off.

Our study has also revealed an inconsistency between the military Services in their commitment level of adherence to knowledge-based practices as mandated by DoDI 5000.02 (DoD, 2013e). In particular, although the evidence continues to mount indicating that programs with immature technology experience cost, schedule, and performance shortfalls, the military Services appear to discount this risk, continuing to allow immature technology into their development programs. Table 8 speaks clearly to this issue, showing that, on average over the past decade, 40 percent of the Army's MDAP CTs rated as sufficiently mature, compared to 57 percent for the Navy and 67 percent for the Air Force.

This article is designed to help decision makers within the Army, Navy, and Air Force, as well as the DoD overall, in understanding the economic impact of the use or nonuse of TRA knowledge-based practices. Through objective, quantifiable measures of performance such as those discussed in this article, we can begin making significant strides toward improving the outcome of our investments in major weapon systems acquisition (Weapon Systems Acquisition Reform Act, 2009).

Author Biographies



Mr. Reginald U. Bailey, a PhD candidate in systems enginering at The George Washington University, is a senior management and engineering consultant with more than 30 years' industry experience specializing in systems and software engineering, project management methodologies, and technology readiness. Mr. Bailey earned his master's degree in systems engineering at The George Washington University, and also holds a bachelor's degree in computer science from the University of California Berkeley.

(E-mail address: baileyr@gwu.edu)

Dr. Thomas A. Mazzuchi is chair of the Department of Engineering Management and Systems Engineering in the School of Engineering and Applied Science, and professor of engineering management and systems engineering, at The George Washington University. He earned his BA in mathematics from Gettysburg College; his MS and DSc in operations research from The George Washington University. Dr. Mazzuchi has conducted research for the U.S. Air Force, Army, U. S. Postal Service, and NASA, among others.

(E-mail address: mazzu@gwu.edu)

Dr. Shahram Sarkani is professor of engineering management and systems engineering, and faculty advisor and academic director of engineering management and systems engineering off-campus programs, at The George Washington University. He designs and administers graduate programs enrolling over 1,000 students across the United States and abroad. Dr. Sarkani earned a BS and MS in civil engineering from Louisiana State University, and a PhD. in civil engineering from Rice University.

(E-mail address: sarkani@gwu.edu)

Dr. David F. Rico has supported major U.S. government agencies for 30 years, and led many Cloud, Lean, Agile, Service Oriented Architecture, Web Services, Six Sigma, Free and Open Source Software, International Organization for Standardization 9001, and Capability Maturity Model Integration projects. He holds a Doctor of Management in information technology from the University of Maryland University College, and is a certified project management professional, agile certified practitioner, and certified scrum master.

(E-mail address: dave1@davidfrico.com)

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Keywords: *Human Viewpoint, Human Systems Integration (HSI), Department of Defense Architecture Framework (DoDAF), Architecting, Acquisition*

Where Are the People? *The Human Viewpoint Approach for Architecting and Acquisition*

Holly A. H. Handley and Beverly G. Knapp

The U.S. Department of Defense Architecture Framework (DoDAF) provides a standard framework for transforming systems concepts into a consistent set of products containing the elements and relationships required to represent a complex operational system. However, without a human perspective, the current DoDAF does not account for the human performance aspects needed to calculate the human contribution to system effectiveness and cost. The Human Viewpoint gives systems engineers additional tools to integrate human considerations into systems development by facilitating identification and collection of human-focused data. It provides a way to include Human Systems Integration (HSI) constructs into mainstream acquisition and systems engineering processes by promoting early, frequent coordination of analysis efforts by both the systems engineering and HSI communities.

« Image designed by Diane Fleischer

The U.S. Department of Defense Architecture Framework (DoDAF) is used by the engineering and acquisition communities to describe the overall structure for designing, developing, and implementing systems (DoDAF Working Group, 2004). DoDAF provides a standard framework for transforming systems concepts into a consistent set of products that contains the elements and relationships required to represent a complex operational system. The use of an architecture framework, such as DoDAF, in the acquisition process can be a critical enabler for systems success since it provides a structured approach to identifying and addressing technical issues early in the systems life-cycle process.

Background

DoDAF was designed to meet the needs of multiple stakeholders, including program managers, systems engineers, and acquisition executives. The architecture framework can be used to provide pertinent information to different communities by employing various viewpoints. Each viewpoint is built by extracting data focused on a specific facet of the system and displaying it to the user through a set of models. Models can be documents, spreadsheets, dashboards, or other graphical representations that organize and display system data. This allows users to focus on specific areas of interest, such as capabilities, data and information, projects, services, and standards, among other viewpoints (DoDAF Working Group, 2010). However, noticeably missing from the list of viewpoints is one that focuses on the human perspective: the Human Viewpoint.

DoDAF is fundamentally about creating a set of models representing the system to enable effective decision making to support systems engineering and acquisition processes. However, without including models that focus on the human perspective, the current DoDAF framework does not account for the human-performance aspects needed to contribute to systems effectiveness and cost. Without this type of information, there is no basis to make informed decisions about the tradeoffs between systems design and human-related issues (Knapp & Smillie, 2010). DoDAF ensures that the architecture descriptions facilitate the creation of systems requirements that will achieve the desired outcomes; however, systems engineers currently do not have sufficient tools to quantitatively integrate human considerations into systems development (Hardman & Colombi, 2012).

This article reviews the Human Viewpoint and then presents a current methodology for identifying and capturing data in the Human Viewpoint models. The relationship between the Human Viewpoint and Human Systems Integration (HSI) is then identified, and support for using the Human Viewpoint in the acquisition process is provided. Finally, an example of how the Human Viewpoint can be used to capture appropriate human system data to support systems design decisions is described.

The Need for a Human Perspective

DoDAF defines different perspectives or views that logically combine to describe a system architecture. A viewpoint provides a self-contained set of models that provides a complete set of data for evaluation consistent with the perspective of the view. When DoDAF was initially released, HSI practitioners argued that without a viewpoint that included the human component of the system, there was no basis in the architecture for analysis of human issues that may impact multiple aspects of the system (Hildebrand & Adams, 2002). For example, analyses that measure the human impact on system performance; cost-benefit analyses that consider the influence of manpower, personnel, and training on total costs; and requirement analyses that include the human specifications to adequately operate and maintain the system all require human-focused data—none of these analyses could be performed with the data currently captured in the framework. With a viewpoint that captures human considerations, these factors could be assessed and addressed early in the acquisition process, similar to technical evaluations. The consideration of human issues can enhance overall systems performance by ensuring efficient and effective use of human resources within the system, ultimately reducing the overall cost of a system (Knapp & Smillie, 2010).

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Developers of the original DoDAF deskbook made an initial attempt to represent humans in the Operational Viewpoint products by including the role of the human and human activities associated with a system (Hildebrand & Adams, 2002). Likewise, in the recent version of DoDAF (version 2.02), human components can be identified under the Performer construct in the Services Viewpoint (DoDAF Working Group, 2010). While both of these attempts allow the identification of the human as an element of the system, simply identifying what functions are allocated to humans does not provide the robustness required to evaluate the human component and its impact on the system; it does not capture the multiple human attributes required to evaluate the ability of a system to support operational requirements and accomplish a mission with the current human configuration. This requires an integrated viewpoint, with a set of models appropriate for analysis from the human perspective.

The consideration of human issues can enhance overall systems performance by ensuring efficient and effective use of human resources within the system, ultimately reducing the overall cost of a system (Knapp & Smillie, 2010).

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With a defined Human Viewpoint, the role of the human within the system is defined and task activities are described at a level useful for analysis. Human characteristics, limitations, and constraints that affect performance are also included in the models, as well as human-centered coordination and metrics. The design of a complete viewpoint allows the impact of the human presence to be evaluated and may be the driver for change in the other views. Without this view, no basis exists in the architecture for analysis and propagation of human issues (Handley & Smillie, 2008).

The Human Viewpoint was developed by an international panel of systems engineering and HSI practitioners (Handley & Smillie, 2008). The goal was to develop an integrated set of models, similar to the other viewpoints, that organized human data for use in the architecture description. These models were also linked to other architecture components, through relationships with the Operational and System Viewpoints, to provide connections to the overall system. The Human Viewpoint contains seven models that include different aspects of the human element, such as roles, tasks, constraints, training, and metrics (Table 1). It also includes a human dynamics component to capture temporal information pertinent to the behavior of the human system. The resulting human perspective provides a basis for stakeholder decisions regarding the human component by linking the systems engineering community to the manpower and personnel integration, training, and human factors communities (Baker, Pogue, Pagotto, & Greenley, 2006).

TABLE 1. HUMAN VIEWPOINT MODELS

Product	Name	Description
HV-A	Concept	A conceptual, high-level representation of the human component of the enterprise architecture framework.
HV-B	Contraints	Sets of characteristics that are used to adjust the expected roles and tasks based on the capabilities and limitations of the human in the system.
HV-C	Tasks	Descriptions of the human-specific activities in the system.
HV-D	Roles	Descriptions of the roles that have been defined for the humans interacting with the system.
HV-E	Human Network	The human-to-human communication patterns that occur as a result of ad hoc or deliberate team formation, especially teams distributed across space and time.
HV-F	Training	A detailed accounting of how training requirements, strategy, and implementation will impact the human.
HV-G	Metrics	A repository for human-related values, priorities, and performance criteria; it maps human factors metrics to any other Human View elements.
HV-H	Human Dynamics	Dynamic aspects of human systems components defined in other views.

Note. Adapted from "Architecture Framework Human View: The NATO Approach," by H.A.H. Handley and R. J. Smillie (2008), *Systems Engineering, 11*(2), pp. 156–164.

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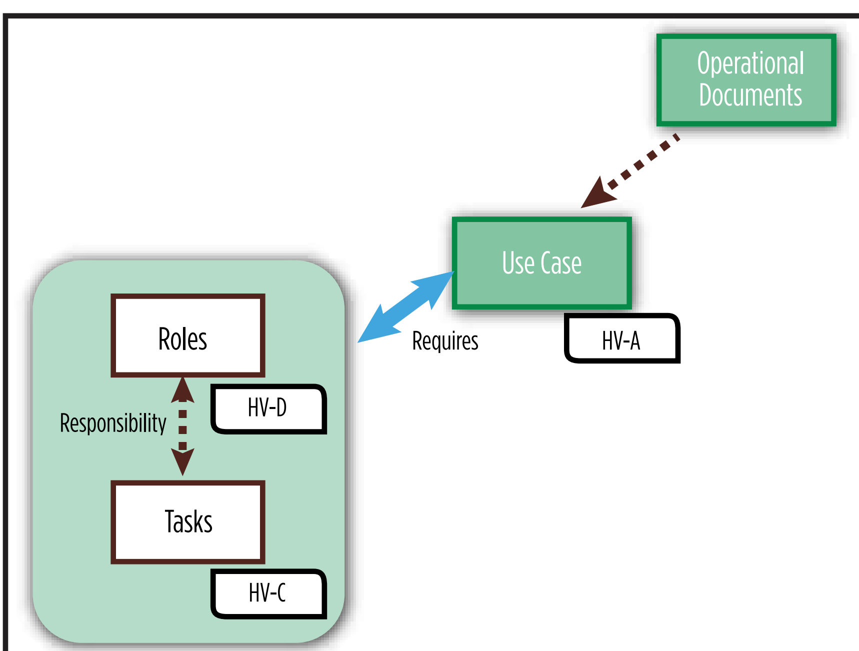
Building a Human Viewpoint

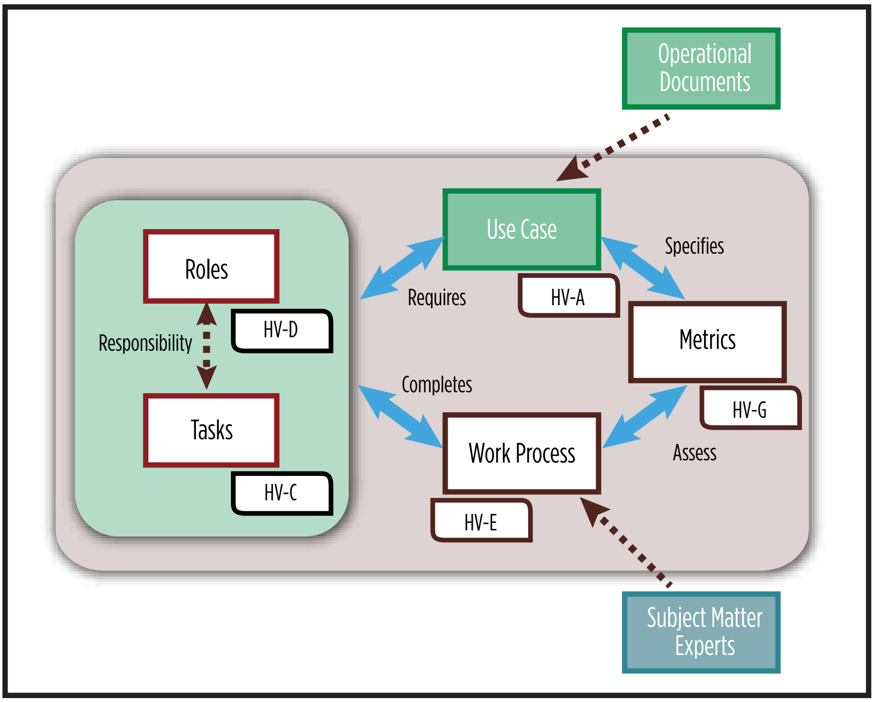
The original Human Viewpoint was defined as a set of required products, but without a prescribed methodology to identify and capture the human data. More recent work has identified how the Human Viewpoint models can be compiled by following a series of steps, broken into stages (Handley & Kandemir, 2013). Each stage represents the development of a critical human performance dimension. The first stage is initiated by visually representing the system concept of operations, using one or more diagramming methods (e.g., concept map, systemigram, rich pictures, etc.). Use cases (HV-A) are then developed that describe the interaction of humans with the operational environment and system components. The second stage develops the human roles (HV-D) and tasks (HV-C), often in tandem. Tasks describe the human activities, usually by more fully decomposing higher level functions. Roles represent job functions or task groupings. The mapping between the two is a key product of the development as it drives manning and training requirements. These first two stages are shown in Figure 1.

FIGURE 1. HUMAN VIEWPOINT AND DEVELOPMENT—STAGES I AND II



The third stage focuses on human interactions and develops a human network, usually represented as a work process (HV-E), which describes the interactions of the roles completing tasks to support the use case. This is another key product of the Human Viewpoint as it describes human activity over time, which is a driver of workload (and overload) for the individual roles. At this stage, role locations can also be included, which is important for designing distributed teams. Metrics (HV-G) representing human performance criteria are also determined. Subject matter experts, often HSI practitioners, are usually consulted at this stage to ensure that the human interactions with the system are accurately represented. This stage is shown in Figure 2.

FIGURE 2. HUMAN VIEWPOINT DEVELOPMENT—STAGE III



In the fourth stage, manning or crew assignments (HV-BI) are completed by mapping personnel to roles based on current qualifications. Additional training (HV-F) requirements are determined based on anticipated knowledge, skills, and abilities requirements. Other human factor constraints (HV-BII) are captured that may impact the human system, such as work cycle and availability. Figure 3 shows the completed Human Viewpoint development process.

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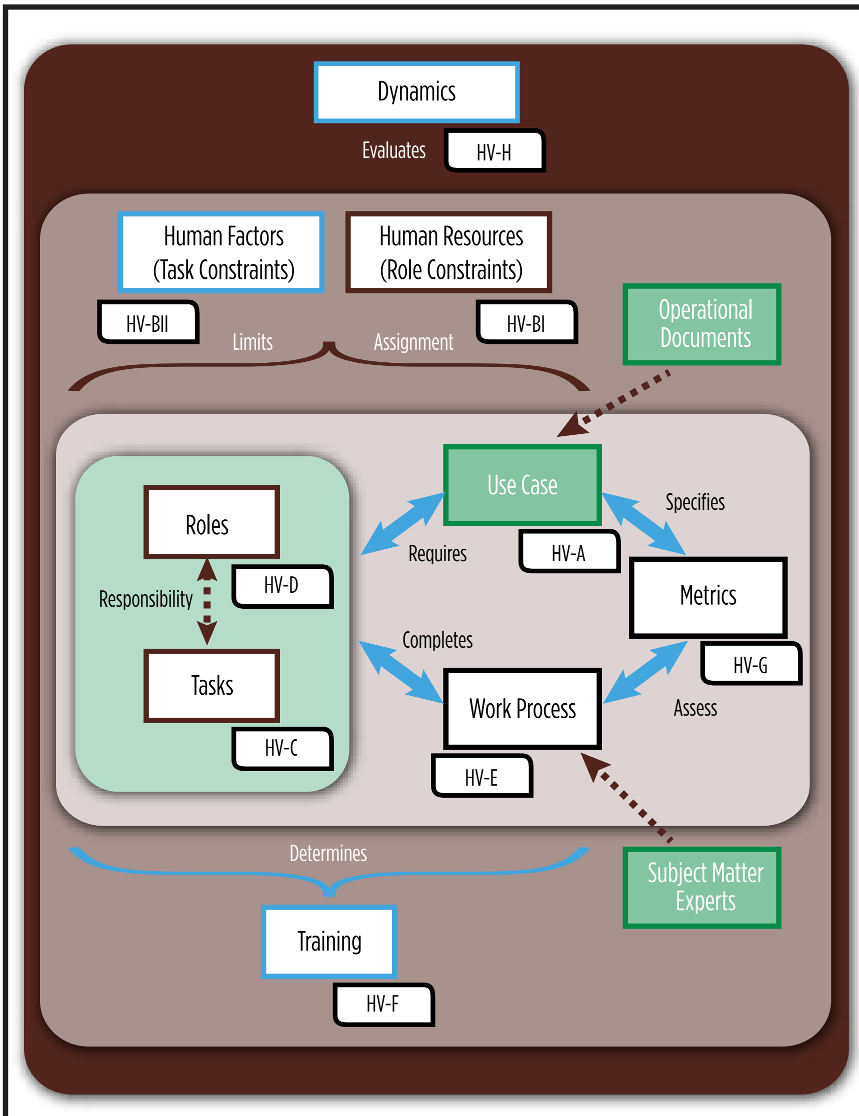
FIGURE 3. HUMAN VIEWPOINT DEVELOPMENT—COMPLETED



After the completion of the individual products, the human dynamics (HV-H) can be used to pull together the information captured in all the products to evaluate the total human system behavior.

For example, an event from the environment may trigger a task (HV-C). The role (HV-D) responsible for the task begins processing it. The role may coordinate with team members (HV-E) for information exchange during processing. The way the task is processed may depend on traits of the actual person fulfilling the role (HV-B) and training completed (HV-F). Use of a system resource (HV-C) to complete the task can also be included. Additionally, other constraints such as human characteristics and health hazards (HV-B) may moderate the performance of the task. Once the task is completed, metrics (HV-G) are used to evaluate the task performance (Handley & Smillie, 2010).

The Human Viewpoint models should capture information about all personnel who interact with the system in any capacity. The operators, maintainers, and support personnel possess particular knowledge, skills, and abilities that must be accounted for in the system design along with their physical characteristics and constraints, just as the technology elements of the system have inherent capabilities and constraints. The inclusion of the human component in the architecture is essential to ensure efficient interfaces between technology elements and the system's intended users, as well as the fit to their physical characteristics.

The initial Human Viewpoint development was done as a "product-based" approach, that is the viewpoint was designed as a set of architecture products that captured the elements representing the interaction of the human with the system. These products were aligned with the other DoDAF Version 1.0 viewpoints and were specifically designed to extend existing DoDAF products wherever possible. For example, elements such as "task" or "role" can be derived from a further refinement of data already captured in the DoDAF Version 1.0 products. However, DoDAF Version 2.0 (initially released in 2009) is a data-based approach with a focus on capturing the data needed for a system, and products or views are rendered as needed from the data for decision making or system design considerations (DoDAF Working Group, 2010). The Human Viewpoint was aligned with the DoDAF Version 2.0 Meta Model (DM2) to produce "Fit for Purpose" views. These views can be used to augment the standard sets of architectural products with human-centered information important to the system description. See Handley (2012a) for a complete description of the implementation of the Human Viewpoint with DoDAF Version 2.0.

The Link Between Systems Engineers and Human Systems Integration

HSI is a disciplined, unified, and interactive approach that integrates human considerations into systems design to improve total system performance and reduce costs of ownership (Cochrane & Hagan, 2001). It is also a strategy to integrate the multiple domains of Human Factors Engineering, Training, Manpower, Personnel, Health Hazards and System Safety. These domains collectively define how the human component will impact systems performance (e.g., mission achievement, safety, and cost), and also define how the system impacts the human component, as reflected in skill gaps and training requirements, manning levels, and workload (Baker et al., 2006). HSI ensures that the needs of the human user are considered throughout the system acquisition process and life cycle, but it represents a departure point for current architecture frameworks, as these human considerations are not captured in the standard DoDAF viewpoints.

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The Human Viewpoint can provide the data and relationships necessary to address HSI concerns that are lacking in current architecture frameworks. For example, the Human Viewpoint can evaluate the anticipated impact of a new system development on the number and type of personnel required; the requisite knowledge, skills, and abilities of the personnel; and the anticipated training that will be necessary to achieve proficiency. To maximize task performance, which affects system performance, information on human characteristics as well as impacts to safety and health hazards should be included in the design, development, and evaluation of the new system. The Human Viewpoint assists in influencing the architecture framework from a "people" perspective—it identifies the effect on the development of the workforce and changes to their working environment by identifying the roles, and therefore personnel, that are affected and the requirements that are necessary to transition the workforce and their workstations to the future system (Hewitt, 2010).

The Human Viewpoint gives systems engineers an additional tool to integrate human considerations into systems development by facilitating the identification and collection of human component data that can be used to improve systems design. The increase in the complexity of systems and the missions they support heighten the need for HSI to be considered early in systems development. Ultimately, the goal of HSI is to integrate considerations of human capabilities and limitations into the design decision-making process, similar to what is done for hardware and software—integration of HSI analysis into the acquisition and systems engineering process is the key to achieving this goal (Pharmer, 2007). The human—the most important and unique system within the system of systems—can also be the weakest link or highest risk in that system; therefore, expressing the capabilities and limitations of the human in the system is imperative (Baker et al., 2006). By developing the Human Viewpoint to be tightly coupled with the DoDAF, the Human Viewpoint provides hooks to include HSI in the evolving systems concept.

The Human Viewpoint assists in influencing the architecture framework from a "people" perspective—it identifies the impact on the development of the workforce and changes to their working environment.

HSI is practiced across the Services, with slightly different definitions for the set of domains. The Army has taken the lead in furthering the development of the Human Viewpoint and has completed the first steps to integrate it into procedures and apply it to systems acquisition. (MANPRINT, or Manpower and Personnel Integration, is the Army's term for the implementation of HSI.) HSI policy information is shared among the Services through the Joint HSI Working Group (2012), which provides a venue for inter-Service collaboration to support DoD HSI initiatives.

Applying the Human Viewpoint in Acquisition

The Human Viewpoint captures human systems data in a programmatic way that closely aligns with systems engineering approaches. This not only supports collaboration between the systems engineering and HSI communities, but helps support the HSI objectives of informing tradeoff analysis; in fact, one of the original drivers for the development of the Human Viewpoint was the concern that the DoDAF views were insufficient to address HSI issues. By explicit modeling, the human elements can be considered early and related closely to the design and implementation of technology (Bruseberg, 2009). In this way, the Human Viewpoint models are appropriate inputs to the acquisition of complex systems.

The application of DoDAF and the Human Viewpoint architecture products is suited to different phases of the Defense Acquisition System (DoD, 2013). The Human Viewpoint models can inform the Joint Capabilities Integration and Development System (JCIDS) analysis starting before Milestone A as capability gaps and approaches to desired end states are identified. Functional requirements emerge by progressing through the Functional Area Analysis (FAA), Functional Needs Analysis (FNA), and the Functional Solution Analysis (FSA; Chairman of the Joint Chiefs of Staff, 2012). Manpower, personnel, and training options can be explored for the conceptual system by including the human data from the Human Viewpoint. Table 2 shows the individual Human Viewpoint models that support the JCIDS process.

TABLE 2. SUPPORT OF HUMAN VIEWPOINT PRODUCTS FOR JCIDS

JCIDS Step	Goal	Supporting Human Viewpoint Models
Functional Area Analysis (FAA)	Tasks to be accomplished	•HV-A provides an overview of objectives •HV-C provides insights into tasks that are required to achieve military objectives •HV-G provides performance standards and metrics for systems tasks
Functional Needs Analysis (FNA)	List of capability gaps	•HV-B1 may identify manpower gaps that cannot be supported by current personnel •HV-D identifies the needed roles to support tasks •HV-E identifies information exchange requirements between roles–may also identify implications of distributed reach-back teams
Functional Solution Analysis (FSA)	Potential integrated DOTmLPF-P (Doctrine, Organization, Training, materiel, Leadership and Education, Personnel, Facilities–Policy) Change Recommendations approach to capability gaps	•HV-B1 provides the ability to conduct strategic manpower tradeoffs and comparisons between potential options •HV-B2 identifies the impact of personnel issues on career progressions (as well as costs) •HV-F identifies the impact on training programs (and costs)
Post Independent Analysis (PIA)	Initial Capabilities Document (ICD)	Complete set of initial Human View product documents

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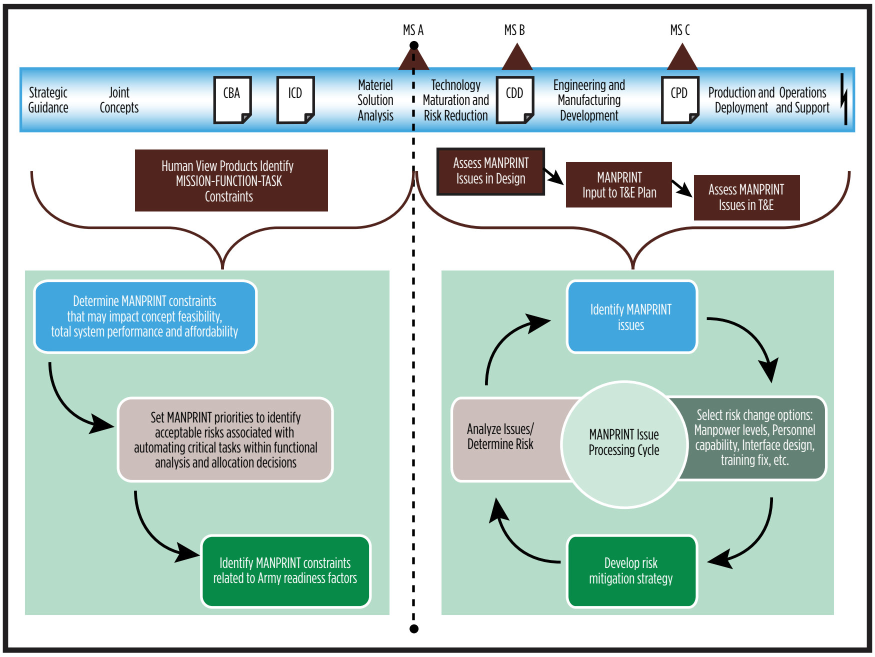
Using the Human Viewpoint to support the pre-Milestone A outcomes facilitates the identification of HSI issues (Baker, Steward, Pogue, & Ramotar, 2008). For example, during the FAA, the HV-C highlights critical tasks that are most likely to be assigned to humans; in the FNA, the HV-B and HV-D assist in the identification of the current and projected personnel required to accomplish those tasks, followed by the FSA, where the HV-F can identify training requirements that may mitigate a manpower gap.

The Human Viewpoint supports the Army MANPRINT program's goals of optimizing total systems performance, reducing life-cycle costs, and minimizing risk of soldier loss or injury by ensuring a systematic consideration of the impact of the materiel design on soldiers throughout the acquisition process (Department of the Army, 2001). Figure 4 shows application of the Army MANPRINT program, both pre- and post-Milestone A. The Human Viewpoint products directly support the MANPRINT processes, which are applied during pre-Milestone A, and can result in risk reduction and fewer changes in the mature system. The MANPRINT issue-processing cycle (post-Milestone A) supports personnel planning for the deployed system by analyzing the work allocation, personnel demand, and required training. It also allows early assessment and mitigation alternatives for personnel survivability (i.e., force protection, safety, and health hazards).

FIGURE 4. MANPRINT ACTIVITIES PRE- AND POST-MILESTONE A



Note. CBA = Capabilities Based Assessment; CDD = Capability Development Document; CPD = Capability Productino Document; ICD = Initial Capabilities Document; T&E = Test and Evaluation; MANPRINT = Manpower and Personnel Integration; MS = Milestone.

In short, HSI issues and systems requirements that impact the human role can be identified pre-Milestone A (Materiel Solution Analysis) using the Human Viewpoint. Then during pre-Milestone B (Technology Maturation and Risk Reduction), the FSA can be revisited to assess the MANPRINT implications of a materiel solution. For example, changes to the initial manpower and personnel assessment, based on a specific materiel option, can be determined by examining the updated architectural products. This may then impact the expected training requirement, and there may also be updates to health and safety issues. During pre-Milestone C (Engineering and Manufacturing Development), the Human Viewpoint products should be updated to align with the final HSI requirements and serve as an authoritative source for formal test and evaluation activities, as well for post-Milestone C Production and Deployment.

The Human Viewpoint provides a way to include HSI in the mainstream acquisition and systems engineering process by promoting early and frequent consideration of human roles. It also provides coordination of task analysis efforts by both systems engineering and HSI teams. Implementing a human perspective can significantly reduce systems risk due to technical design problems by communicating information about the needs and constraints of the human component and ensuring optimal performance and safety.

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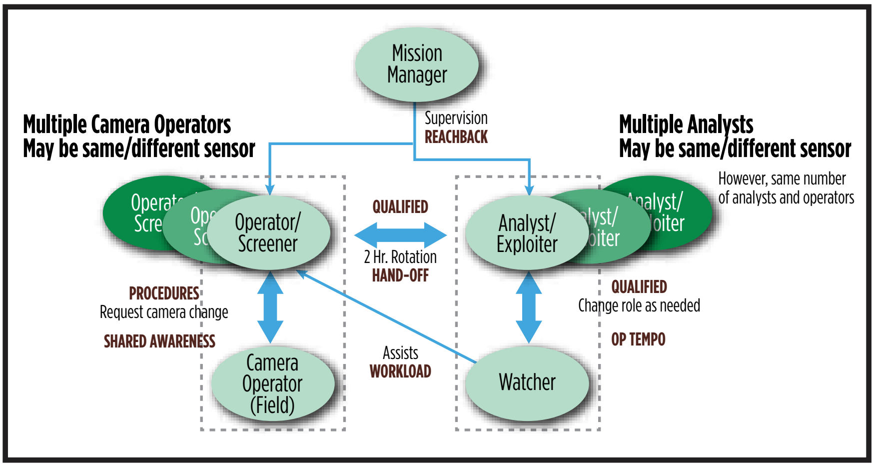
Supporting Analysis and Design

It is not necessary to complete the full set of Human Viewpoint models to benefit from a human architecting effort. Each individual model captures a "snapshot" of different aspects of the human system and can add value to the architecture description. For example, the HV-C captures the human-level activities of a system. These tasks can be described in terms of a sequence diagram (i.e., a temporal ordering of the tasks). This can give an indication of how well a given sequence of tasks will perform, and the performance predictions for alternative sequences of tasks can be compared. Analyses with single products can also provide insights by comparing "as-is" and "to-be" architectures (Handley, 2012b). For example, an analysis of the role assignments (HV-D) due to task changes may result in recommendations to reallocate tasks to other roles based on workload, skill requirements, or locations. For network-based systems, an analysis of the HV-E may result in different coordination requirements for distributed team members to define responsibilities and information sharing. Figure 5 illustrates the interactions between roles on a distributed team and identifies parameters that may be impacted. Even using a subset of the Human Viewpoint models provides the opportunity to capture and organize diverse human information to assess design decisions and recommend improvements.

FIGURE 5. EXAMPLE OF A HUMAN NETWORK (HV-E)



Note. Adapted from "Human View Considerations of the Intelligence Crew for the Multi-Intelligence Platform Long Endurance," by H. A. H. Handley and C. Kandemir, 2013, Alion Science & Technology Final Report. Hr = Hour; OP = Operations Tempo.

Having a dedicated Human Viewpoint allows evaluation and adjustment of the human parameters associated with a system. This analysis can be completed initially with the data captured in the Human Viewpoint and then associated with other architecture viewpoints for a more comprehensive analysis. For example, multi-intelligence, multisensor platforms are designed to carry a variety of sensor types to provide persistent surveillance for long-duration missions (Kerish & Perez, 2010). The dramatic increase in available sensors over a longer period of time demands a more agile and adaptable crew capable of rapidly processing sensor data from multiple sources. Because the frequency and combinations of sensors can vary, the crew will need to be able to adjust to different types and combinations of sensors with minimum disruption to its organizational processes. The Human Viewpoint can be applied to generate alternative crew designs for different sets of constraints, and then evaluate the potential configurations to assess the organizational performance. As the sensor combination shifts, personnel are reassigned to new tasks, based on the constraints of required knowledge, skills, and abilities, while performing within an acceptable workload threshold. For each configuration, both the impact to the system design and compliance with HSI requirements can be evaluated.

In this context, the Human Viewpoint can be used to evaluate Manpower issues (the impact of a fixed crew size responding to varied task-loading over time); Personnel issues (the impact of fixed specialties responding to varied sensor types); and Human Factors issues (the impact of operational tempo on task assignment). The Human Viewpoint analyses can evaluate options such as increased cross training and varying skill levels to improve the adaptability of the crew to meet system needs. By identifying the attributes and parameters used to define the crew, a data map can be created that defines the data to be captured in each product, as well as the relationships between the variables of interest (Figure 6). These relationships can then be further explored to identify both limitations and opportunities for change.

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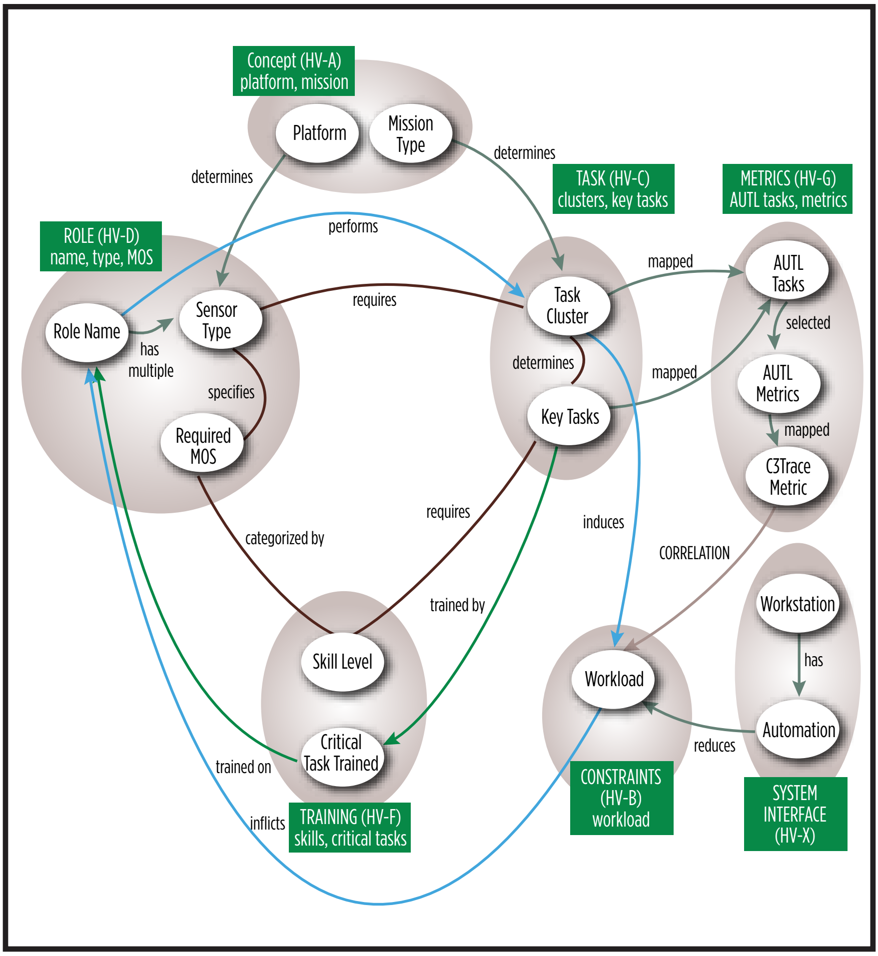
The Human Viewpoint analysis of the intelligence crew supporting long-endurance, multisensor platforms facilitated the design of alternative operator and task arrangements by first capturing the human systems requirements of the baseline configuration. Next, the operator requirements for different crew configurations were determined by evaluating the roles, tasks, and work processes with different sets of constraints. Finally, a simulation model was used to evaluate the effectiveness of the crew in the mission environment (Handley & Kandemir, 2013). After evaluating the impact of the change, the candidate crew configuration was either accepted as a viable alternative, or rejected and other parameter variances explored.

Conclusions

Humans play a pivotal role in the performance and operation of most systems, because systems must be supported by sufficient manpower, and personnel must be adequately trained to operate the system. Therefore, the absence of a human perspective in the architecture framework leaves a gap in both the systems architecting and acquisition processes. The Human Viewpoint organizes information and provides a comprehensive and understandable representation of human capabilities related to expected performance. It provides a basis to inform stakeholder decisions by enabling structured linkages between the engineering community and the HSI communities. Finally, it provides a fully integrated set of products that can be used to inform and influence system design; it facilitates human systems tradeoff analyses; and it ensures the human component has visibility as a routine part of the systems design and acquisition processes.

FIGURE 6. HUMAN VIEWPOINT DATA MAP



Note. AUTL = Army Universal Task List; C3TRACE = Command, Control, and Communications: Techniques for the Reliable Assessment of Concept Execution Modeling Environment; MOS = Military Occupational Specialty.

Author Biographies

Dr. Holly A. H. Handley is an assistant professor in the Engineering Management and Systems Engineering Department, Old Dominion University, Norfolk, VA. Her education includes a BS in electrical engineering from Clarkson College, an MS in electrical engineering from the University of California at Berkeley, and an MBA from the University of Hawaii. She received a PhD in information technology and engineering from George Mason University in 1999. Dr. Handley is a Licensed Professional Engineer.

(E-mail address: hhandley@odu.edu)

Dr. Beverly G. Knapp is a research psychologist and program analyst who is also the deputy director for Manpower and Personnel Integration, Headquarters, Department of the Army (HQDA), G-1. She is also an advisor to the HQDA G-2 Science and Technology Team, representing cognitive processes and human performance issues for intelligence systems. Dr. Knapp obtained her master's degree in human factors and a doctoral degree in applied-experimental psychology from The Catholic University of America in Washington, DC.

(E-mail address: beverly.g.knapp.civ@mail.mil)

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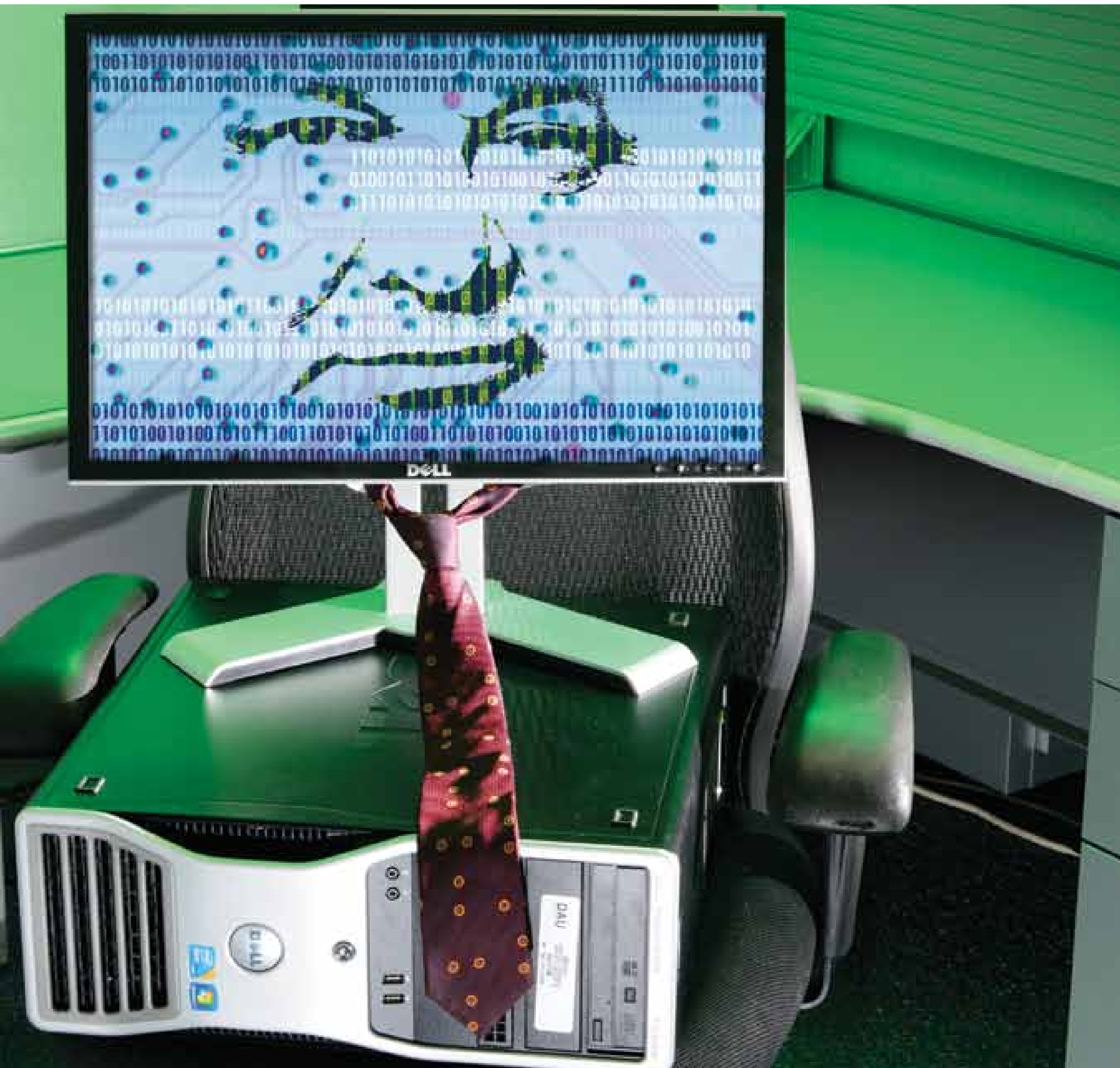

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Featured Book

Adapting to Flexible Response, 1960–1968

Series:
History of Acquisition in the Department of Defense, Volume II

Author:
Walter S. Poole

Publisher:
Office of the Secretary of Defense, Historical Office

Copyright Date: 2013

ISBN: 978-0160921834

Hard/Softcover:
Hardcover, 467 pages

Reviewed by: Dr. Roy L. Wood, Dean, Defense Systems Management College, Defense Acquisition University

Review:

John F. Kennedy had won the 1960 Presidential election and entered office with a strong and growing Soviet menace held at bay by his predecessor's threat of mutual assured nuclear destruction. The Cold War strategy of containing communism also meant fighting surrogate brush wars and conducting bold—sometimes rash—covert operations. Many of these were underway in Europe, Southeast Asia, and in the Caribbean. Vietnam was quickly becoming a focal point for U.S. military support and intervention in this ideological battle of wills. For the United States, 1960–1968 was a time of strategic change abroad and brewing social upheaval at home. This was the environment President Kennedy stepped into when he took the oath of office in 1961.

Meanwhile, within the Pentagon, under the newly appointed Secretary of Defense Robert McNamara, change would likewise become the order of the day. Supporting President Kennedy's shift from a military strategy of mutual destruction to one of "flexible response" meant moving away from near total reliance on nuclear weapons to building capable new conventional forces and weapon systems. This tumultuous period of change and refocus is the backdrop of Walter Poole's book, *Adapting to Flexible Response, 1960–1968*. This important book is the second volume in the acquisition series from the Office of the Secretary of Defense, Historical Office (released in 2013).

Poole discusses the acquisition of new systems to support the flexible response strategy. Some of these included producing and fielding helicopters in large numbers and in direct combat roles for the first time, continuing to build nuclear submarines and surface ships, and creating fleets of aircraft including the F-111 fighter-bomber and heavy cargo lift C-5A. To produce these systems, defense acquisition management changed dramatically under McNamara's Planning, Programming, and Budgeting System and Five Year Defense Plan. The Office of the Secretary of Defense and McNamara's "whiz kids" applied systems analysis to requirements and acquisitions, and encroached as never before on what had previously been Service prerogatives.

Poole's book masterfully sets the stage for this complex drama and describes the forces inside and outside the Pentagon that drove defense acquisition during this period. He then dives deeply into individual weapon systems acquisition, creating rich case studies that give us glimpses into the policies and practices that went well—and those that did not. For instance, he compares the successful C-141 with the troubled C-5A programs to provide long-range airlift and describes the Army's fascinating political struggle to choose between the M-14 and the AR-15 to outfit its infantry. He discusses Navy shipbuilding and the love-hate relationship with Admiral Hyman G. Rickover and nuclear power, as well as the reliability issues of the Navy's "3-T" missile (Talos, Terrier, and Tarter) and the move toward a "standard missile" replacement program.

Poole's tome is highly recommended reading for today's acquisition professionals. Many of the challenges Poole highlights from programs in the 1960s will seem familiar to those encountered in today's programs—stringent requirements, tight schedules, emerging technologies, a risk-averse bureaucracy, and an assertive Congress that purports to "help." Set in a tumultuous period of evolving threats, international crises, domestic social unrest, and Pentagon bureaucratic struggles, there are important lessons to be learned and insights to be gained from Poole's well-written and thoroughly researched history.

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Defense ARJ
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Author Due Date	Publication Date
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