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BLENDING SYSTEMS ENGINEERING PRINCIPLES AND SIMULATION-BASED DESIGN TECHNIQUES TO FACILITATE MILITARY PROTOTYPE DEVELOPMENT

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ABSTRACT

Tactical communications represent a critical skill set to military training at the individual service level and to the joint military community. As the complexity of the operational environment increases, the methods and devices employed to address tactical communications training follow suit. One mitigation approach incorporates simulation tools by merging live training elements with virtual, or simulated, training devices. Thus, integrating live and virtual components is particularly important to the tactical communications training domain. A logical step in the advancement of live-to-virtual (LV) communications is the development of a device capable of merging, managing, and allocating multiple requests for live radio resources in a dynamic live, virtual, constructive (LVC) configuration. This paper details the application of systems engineering principles and simulation-based design to the development of a prototype Integrated Live-to-Virtual Communications Server (ILVCS). A detailed discussion of the developmental approach and its impact upon cost, schedule, and technical risks is provided.

1 INTRODUCTION

Current methods for integrating LV communication assets within military training environments provide connectivity, but require a one-to-one match between the number of bridged circuits and the number of relay radios (Lackey et al. 2007). In essence, an operational (live) radio must be statically allocated for each circuit bridged (see Figure 1).

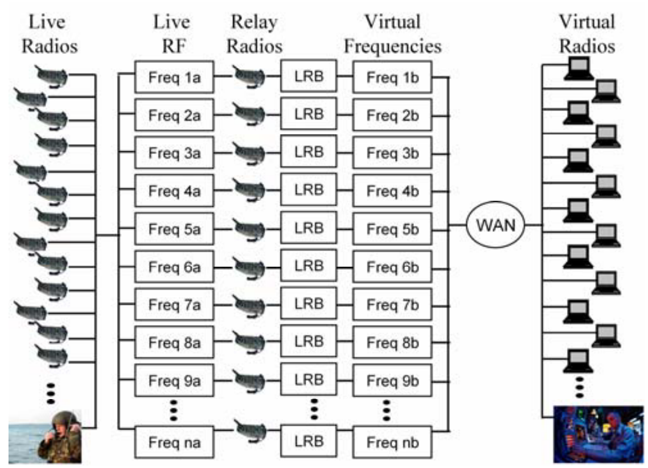

Figure 1. Current LV bridging communications architecture (Lackey et al. 2007)

The Naval Air Warfare Center Training Systems Division's Concept Development and Integration Laboratory revolutionized the methods and tools for providing LV voice communication links. Freedom from a required one-to-one match of live radio to bridged circuit is facilitated by the architecture shown in Figure 2. The number of relay radios can be significantly reduced without impacting system performance. Such reductions in operational hardware can provide meaningful benefits to the U.S. armed forces training commands and offer an estimated equipment savings of 25%-53% and an estimated cost savings of $150,000.00 - $630,000.00 per training site.

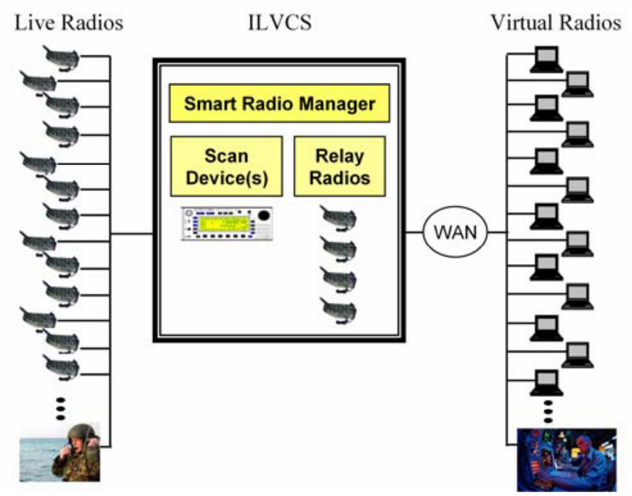

Figure 2: Integrated Live-to-Virtual Communications Server architecture (Lackey et al. 2007)

By applying systems engineering principles and simulation-based design techniques, a prototype device was developed and is now serving as the foundation for an initial deployment to the United States Marine Corps in late 2007. Further military implementations are under investigation and planned for 2008-2010.

This paper begins with a summary of systems engineering approaches and previous applications of modeling and simulation to tactical communication systems. Next, specific challenges identified during the initial development phases of an Integrated Live-to-Virtual Communications Server are given. A detailed description of the systems engineering approach and discrete event simulation (DES) techniques applied to address these challenges follows. Finally, the quantified results of this effort and the products developed are discussed.

2 SYSTEMS ENGINEERING APPROACHES

The waterfall method, once the most commonly used systems engineering approach applied to major acquisition projects (Defense Acquisition University 2001), involves a series of steps completed in succession (see Figure 3).

Typical steps in this approach include: requirements definition, design, build, test, and deploy. A review of project progress and requisite documentation after each step determines whether the project is ready to move forward, but minor overlap may occur. While this method was effectively applied to many large-scale development efforts, clear drawbacks to this method exist when applied to concept formulation and initial development. The waterfall approach fails to allow for a prototyping phase, nor does it accommodate new requirements (Sommerville 2001). Additionally, by its nature it is time consuming and costly (National Office for Integrated and Sustained Ocean Observations 2005).

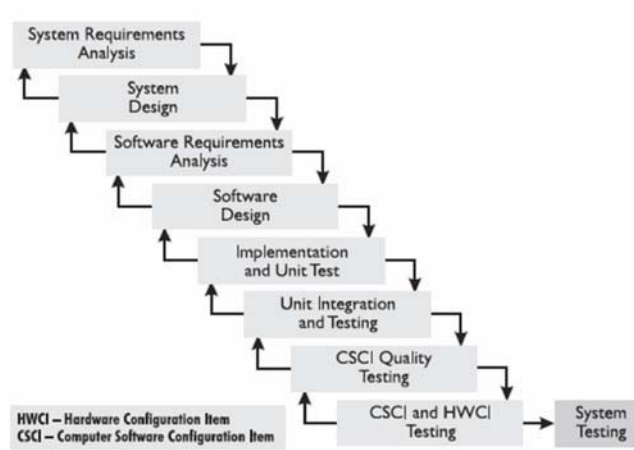

Figure 3: Typical Waterfall Systems Engineering Phases (Schaeffer 1998)

The classic waterfall method was formerly employed by the Department of Defense (DoD), but gave way to a new method termed the spiral approach (Defense Acquisition University 2001). Several years ago, the DoD implemented a new systems engineering approach based upon a recursive process. This method provides a comprehensive approach that is applied sequentially by integrated teams (see Figure 4).

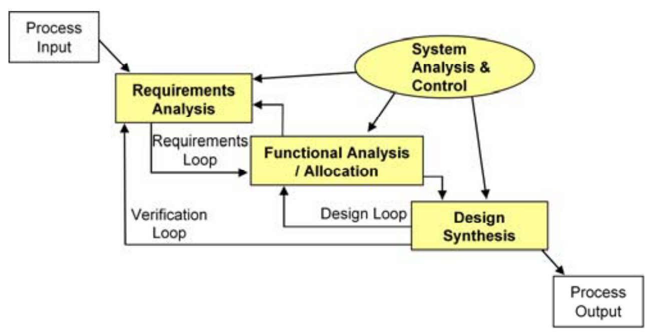

Figure 4: DoD Systems Engineering Process (Defense Acquisition University 2001)

Process input consists of user needs, objectives, requirements, and project constraints. Requirements analysis translates the process inputs into functional and performance requirements. Functional analysis decomposes the requirements identified above into lower-level functions. Design synthesis defines physical and software elements required to create the product. Each element must support at least one functional requirement.

If the functional analysis indicates a need to revisit requirements, then the requirements loop is followed. The design loop provides a means to revisit the functional analysis phase if necessary. The verification loop assesses whether the results of the design satisfy the original requirements. System analysis and control provides balance to the system. This module is responsible for decisions based upon tradeoff analyses, development of schedules, and ensures that the required technical disciplines are integrated into the effort. Ultimately, the process output for each cycle depends upon the level of development, but includes the system decision database, the system architecture, baselines, and specifications (Defense Acquisition University 2001).

The DoD spiral approach provides an analysis phase prior to each developmental and testing phase, and allows for both changing requirements and prototyping. The full implementation of this method, including progress reviews and documentation, is intended for large-scale development projects.

A third method, based upon the spiral approach, is the Human Performance System Model (HPSM) (Human Performance Center 2003). This method involves four phases that are intended to be applied in succession as many times as required. The four phases include define requirements, define solutions, develop components, and execute and measure (see Figure 5).

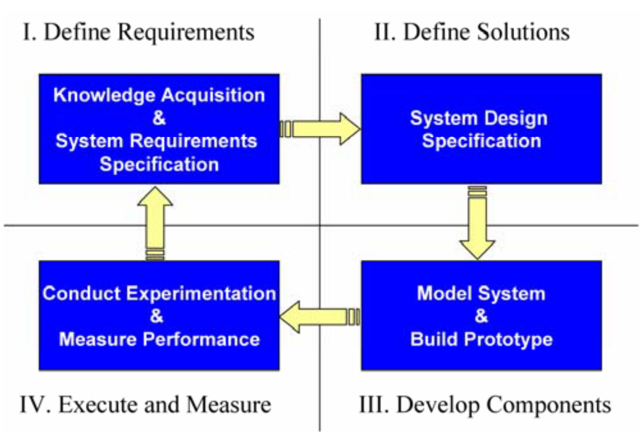

Figure 5: Human Performance Systems Model (Human Performance Center 2003)

Phase I defines requirements by gaining knowledge about the system and specifying performance and functional requirements. The next phase defines solutions by generating the system design based upon the requirements from Phase I. The system design then drives the development of components in Phase III. Finally, Phase IV evaluates the performance of the components developed by comparing the actual system performance to the predefined performance specifications (from Phase I). Insight gained from each model iteration is leveraged into the next cycle.

This method offers the benefits of the DoD systems engineering approach, but is more applicable to smaller projects and research efforts. The HPSM provides structure and accounts for the four basic systems engineering phases. However, it reduces the complexity of model execution compared to a large-scale spiral process. The concise nature of the four quadrant model lends itself to adaptation for smaller efforts. Thus, HPSM offers flexibility that is beneficial to prototype development.

3 APPLICATION OF SIMULATION TECHNIQUES TO TACTICAL COMMUNICATION SYSTEMS

Historically, the military has used modeling and simulation to test new tactical communications system configurations (Baker, Hauser, and Thoet 1988). Baker et al. (1988) discuss the importance of understanding the performance of underlying radio networks that support tactical radio communications in order to facilitate prototype development. Simulation analyses for the purpose of facilitating design decisions and prototype development is also discussed by Kolek, Rak, and Christensen (1998). The Battlefield Communications Network and Tactical Engagement Simulation program demonstrated how simulation could be applied to performance analysis of radio networks (Kolek et al. 1998).

Network analysis is another military application of simulation described in the literature. The US Army developed the Information Flow Design and Evaluation Tool that provides prioritization, allocation, planning, and management of division-level tactical network resources (Hill et al. 2001) through the application of DES. The Network Warfare Simulation (NETWARS) program aims to model military, federal, state, and local civilian agencies to improve planning and decision processes during a large-scale crisis event (Murphy and Flournoy 2002). NETWARS, a network-modeling tool for the U.S. armed forces, provides tools to model, analyze, and assess network traffic and information flow.

Simulation has proven its value to tactical communications technology developers and decision makers. During research and development of emerging communications technology, simulation can be used to support design efforts and component development. Simulation engines have also been used to drive network analysis and operational planning tools. Modeling and simulation techniques have application to the full range of design, development, and deployment of tactical communications tools.

4 PROTOTYPE DEVELOPMENT

Although countless challenges face any research effort, five fundamental challenges arose during the initial phases of the ILVCS development. First, since the system in this case encompassed the entire LV communication network, the level of system complexity was extremely high. Inserting an additional subsystem into the architecture required a thorough investigation of the component subsystems and their interactions. Second, no persistent system of the communications network under investigation was available. No test-bed existed that would support experimentation on the scale required, and experimentation during actual training events was not feasible. Due to the lack of a persistent system, there was a lack of doctrinal requirements and design documentation, and a shortage of available data. This third challenge led to a desire for clear documentation and the establishment of extensible prototype software and hardware that would facilitate future development and production. Finally, cost and schedule constraints demanded a prudent approach to accomplish the research and development goals. Identification of the ILVCS developmental challenges motivated the pursuit of a process to maintain balance between technical goals, cost, and schedule constraints. The following section details the process implemented.

4.1 Developmental Approach

The methodology employed was based upon a systems engineering approach implemented by the U.S Navy's Human Performance Center. Figure 5 depicts the HPSM (Human Performance Center 2003) adapted for this effort. Three iterations of this model were necessary to complete the proposed research. Spiral 1 focused on the simulation of the existing system. Spiral 2 redirected the simulation focus to alternatives to the existing system configuration. The third spiral developed a prototype device based upon the outcomes of the previous spirals. See Figure 6 for a graphical representation of the development spirals.

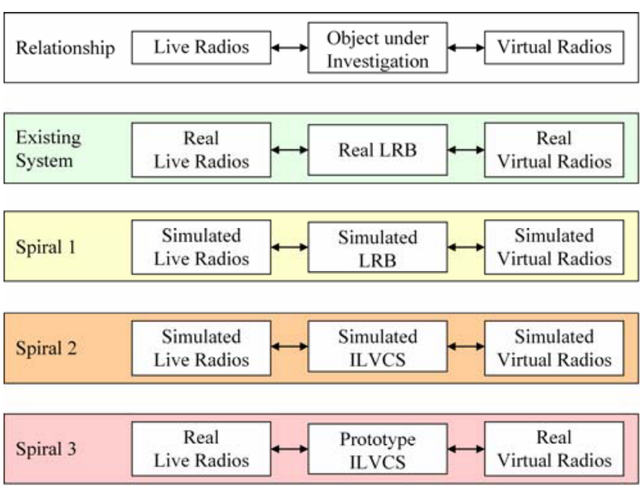

Figure 6: ILVCS Research and Development Process

4.2 Spiral 1: Simulated Live Radio Bridge (LRB) Configuration

The first spiral simulated the existing LRB configuration (see Figure 1). Requirements derived in this spiral drove the efforts during the three development spirals. The requirements included the definition of a use case that was based upon exercise and communication plans from various LVC training events. An exercise length of four hours and a total of 40 bridged circuits were defined for this use case. For this configuration, it is important to note that each bridged circuit required an operational radio resource. Communications in this environment were uni-directional and zero loss of transmissions was strictly enforced.

Following the use case development and requirements definition, an object-oriented DES was designed to model the current LRB capability. Unified Modeling Language (UML) tools supported the design of the DES. Creation of class and state diagrams facilitated the development of the DES software design by clarifying component interactions and life cycle processes of entities.

DES development included extensive input modeling. Nine sets of communications data collected during military training exercises were available for analysis. After analyzing eight out of the nine data sets to gain insight into the characteristics of tactical voice communications, the remaining data set was reserved for model verification purposes.

In addition to the number of transmissions passing over each circuit, transmission lengths and interarrival times were of particular interest. The analysis of military communications data provided insight into the attributes of transmissions passing through the LRB system. Input models developed in Spiral 1 were leveraged for all simulation models analyzed during the ILVCS research effort.

Programming of the DES was based upon the design defined in Phase II of Spiral 1. Java served as the programming language and the model was constructed using the Discrete Event Simulation MOdeling – Java (DESMO-J) application programming interface (API).

Model verification included informal peer reviews by the original developers of the LRB technologies. Structured model comparisons were based upon DES output analysis. Thirty replications of the DES using the input models developed were compared to the model performance using the reserved data set. No significant difference was indicated at an alpha level of 0.05. Upon model verification, the LRB DES served as the baseline for alternative comparisons.

4.3 Spiral 2: Simulated ILVCS Configuration

Spiral 2 simulated the ILVCS configuration (see Figure 2). One feature of the use case was modified for Spiral 2: the number of relay radio resources within the system. The requirement of the ILVCS system was to reduce the number of resources without reducing the quality of service (zero loss of transmissions). This single change significantly impacted the DES design of the alternative ILVCS system(s).

In order to reduce the number of relay radios, a mechanism for detecting transmissions over live radio frequencies (RF) had to be provided. Multiple alternative configurations were considered, but two were deemed feasible. The first alternative involved creating a bank of scanning radios that monitor subsections of the RF spectrum in addition to maintaining a bank of relay radios for signal transmission. The second option sought to identify a device that would monitor a defined portion of the RF spectrum in order to detect live RF transmissions.

Each alternative design was based upon the design in Spiral 1 and modified as required. The modified designs generated in Spiral 2 and input models developed during Spiral 1 served as the foundation for simulation development and programming. The ILVCS simulation models leveraged the LRB DES previously programmed in Java using the DESMO-J API.

Model verification was conducted in the same manner as Spiral 1 for each ILVCS configuration. No significant difference at an alpha level of 0.05 was indicated between the performance of the simulated ILVCS configuration using the input models developed in Spiral 1 and the reserved data set. Scenario comparison of the alternative configurations assisted in determination of which ILVCS design to implement. Using common random numbers for the DES input ensured that the same random numbers were used for the exact same purpose in each alternative. Thus, the observed differences between models were not due to variance in transmission attributes, rather differences between model configurations (Law and Kelton 2000). No significant difference was indicated at an alpha level of 0.05 between the two configurations. However, due to reduced system complexity and cost, the second alternative was chosen for prototype development. In essence, the monitor configuration offered a more elegant and cost effective solution.

Experimental results indicated that the ILVCS-Monitor configuration may significantly reduce the number of relay radios required to support the requirements specification from Spiral 1. Output analysis of the ILVCS-Monitor DES indicated that depending on exercise length and if the number of bridged circuits ranges from 20-40, the number of relay radios could be reduced by 25%-53%. Assuming an estimated cost of $30,000.00 per relay radio, the cost savings ranges from $150,000.00 - $630,000.00 per training site.

4.4 Spiral 3: ILVCS Prototype Device

Finally, the third spiral of the systems engineering process resulted in the design and development of a prototype ILVCS device. This prototype, capable of determining the number of relay radios required to support a given exercise, also dynamically allocates those resources during a LVC training event.

The requirements, system architecture, and both software and hardware designs were based upon the products and results from Spiral 2. Leveraging existing LRB software source code and hardware components facilitated the development of the ILVCS prototype software and hardware. Modifications to the components leveraged occurred as necessary in order to support the prototype device development.

Testing and evaluation of the prototype verified device functionality and performance. The ILVCS was shown within a laboratory setting to sufficiently meet the defined requirements.

5 RESULTS

The systems engineering method described above provided structure to the analysis of a highly complex system, and led to the development of a new subsystem. By dividing the effort into three spirals, the current system capabilities were clearly defined and alternative configurations could be considered. The phases within each spiral added another level of organization to the effort, and provided a way to assess and convey progress toward technical, cost, and schedule goals.

While the adaptation of the HPSM provided a systems engineering blueprint for the overall effort, DES techniques made significant contributions. Without an existing system, analysis and experimentation were not possible. DES provided a means to demonstrate subsystem interactions and to experiment with various configurations. The DES input modeling process led to use case definition and added much needed insight to the nature of tactical communications. By simulating the tactical environment, a deeper understanding of tactical communications resulted in the refinement of system requirements, design recommendations, and served as the foundation for the prototype developed.

By drawing upon the strengths of DES to reduce technical risks, cost and schedule risks were also mitigated. Simulation-based design allowed for comparison of multiple alternative configurations prior to hardware procurement and assembly. The results from the DES study influenced procurement choices, and provided an opportunity for "what-if" analyses prior to construction. It is estimated that the utilization of DES analysis techniques afforded a cost savings of 33% in hardware procurement, 46% in software development, and 75% in system analysis.

The key element in the hardware cost savings involved the monitor device. Two models were available: one model provided core scanning capabilities, while the second model expanded the capabilities of the core scanning features, but required an additional investment of approximately $ 25,000.00. DES analysis confirmed that the core scanning capabilities were sufficient or exceeded the requirements defined for the ILVCS effort. The hardware cost savings provided were compared the actual procurement cost of approximately $75,000.00 for the ILVCS prototype equipment.

Significant software development cost savings resulted from analyzing LV communication network behavior observed via the DES. The savings were calculated by estimating the number of labor hours required to complete the software programming (950 hours). Next, specific components of the software code that were affected by decisions resulting from DES analysis were considered. With input from the software development team, the number of labor hours saved was then estimated (800 hours). A comparison of the number of labor hours saved and the actual number of labor hours resulted in an estimated software development savings of 46%.

An assessment of the time required to analyze the communication system represented by the DES indicated significant savings. Without a persistent communication system in existence, observation and data collection were severely limited. The limited number of exercises made available was utilized for data capture and use case definition in order to construct the DES. Approximately 9 months was required to develop the DES. It was estimated that 36 months would be required to observe a sufficient number of live exercises if DES analysis was unavailable. A 75% savings in time to analyze and model system behavior resulted.

Frankly, the quality of work resulting from this research effort could not have been achieved without the use of DES. Without an existing system to use for experimentation, system analysis would have been severely impaired. The durations of the first and second spirals were reduced by approximately 50% and 80%, respectively. Utilizing DES to fill the need for an experimental system supported prototype development within a constrained schedule. DES significantly contributed to reducing technical, cost, and schedule risks.

The products (see Table 1) of this effort are available for future use. The products include requirements specifications, system design documentation, DES tools, and prototype hardware and software. Research results in the area of input modeling for tactical communications, and an innovative algorithm for predicting resource requirements are available for emerging development efforts and operational experimentation.

6 CONCLUSIONS

Applying systems engineering principles and simulation-based design techniques benefits prototype development. They are particularly adept at addressing issues found in complex systems and their associated subsystem components. Based upon the developmental challenges identified at the beginning of this effort, the application of a systems engineering approach was a natural choice. The three spirals defined provided structure to the overall effort. The phased approach (requirements definition, design specification, component development, and performance measurement) within each of the three spirals provided continuity throughout the entire development cycle. Incorporating DES techniques assisted in the conceptualization of the system under investigation, the derivation of functional requirements, and comparison of design alternatives. This research effort illuminates the utility of systems engineering principles and simulation-based design techniques when applied to advanced military technology development and prototyping initiatives.

Table 1. Products Resulting from Each Spiral of the System Engineering Process

Phase	Product
Spiral 1	LRB system requirements DES input models LRB DES design LRB DES Model verification Initial ILVCS recommendations
Spiral 2	ILVCS system requirements DES input models ILVCS DES design ILVCS DES Experimental results Initial ILVCS recommendations Refined prototype ILVCS recommendations
Spiral 3	Prototype hardware and software requirements Prototype design Prototype ILVCS device Experimental results Production recommendations

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