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An Agent-based Approach to Evaluating the Impact of Technologies on C2

C2 Analysis, C2 Modeling and Simulation, Cognitive Domain Issues

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ABSTRACT

The dynamic nature of hostile, urban environments has resulted in an increased interest in novel command and control (C2) technologies and associated tactics, techniques, and procedures (TTPs). However, the introduction of new technologies to support C2 significantly impacts performance and effectiveness of military forces. The goal of our research was to support the assessment of novel Communications, Command, Control and Intelligence (C3I) technologies that addressed various challenges of Military Operations in Urban Terrain (MOUT). Our novel approach combined the strengths of field assessment with virtual and constructive simulations, which can quantify the effects of technologies and associated TTPs that span a wide range of capabilities; including sensing, situation awareness/command and control (SA/C2), and shaping components. These evaluation capabilities are complemented by support for optimizing TTPs and organizational structure to improve performance across a variety of metrics (e.g. mission completion time, execution tempo, team task load, etc.). Initial assessments were validated by comparing results from field studies and simulations, which confirmed that our approach identified force-multiplying effects of emerging technologies.

Introduction

Recent events in Iraq have clearly demonstrated the lethality of asymmetric threats on United States (US) forces. Furthermore, MOUT operations (such as cordon and search or patrols, Table 1) often require highly decentralized small unit operations which pose numerous challenges to ground forces in their ability to successfully complete their mission. Advances in C2 technologies are of critical importance to combat the increasing challenges imposed by this dynamic, high-risk environment. However, the benefits of advanced technologies are not necessarily apparent and the preeminent use of these systems is not well known.

Table 1 – Examples of potential MOUT missions

Fixed Site Security	Dismounted Patrol	Cordon and Search
Fortified checkpoints	Roving patrols	Recon and secure routes
Guard towers	Ad-hoc checkpoints	Area security

There is a great need for analysis on the effectiveness of novel C2 technologies and new TTPs on mission performance. Results of modeling and simulation can yield significant evidence on the most effective utilization of such systems, and indications of where future gains are to be made in the development of these technologies. To address this need, we developed an approach for the evaluation of technology in complex environments. We present the application of our approach on the Sensing and Patrolling Enhancements Yielding Effective Security (SPEYES) system and discuss the implications of our analysis on the development of future technologies.

In the following sections, we present relevant background on technology evaluation and SPEYES. We then describe our approach to provide context for our modeling effort and discuss the simulation test bed we used for our experiments. We then present our

computational model, discuss the design of our experiments, and describe the results and implications of our analyses.

Background

Technology Evaluation

Figure 1 illustrates how new technology effects can manifest themselves at multiple levels in a complex mission (Linegang, 2006). For example, a new information system may improve the performance of the direct users of that system, but ultimately produce information bottlenecks that result in a decrease in overall “global mission performance” of the team; or conversely, a new technology may yield minimal benefit for the direct users of the technology, but generate substantial benefit for indirect users in another portion of the team. To conduct a comprehensive evaluation of new technology for mission performance in a command and control environment, one must be able measure performance effects at several levels of granularity, including 1) measurement of direct and indirect technology impacts on command and control decision-making, and 2) measures of technology impacts on team performance in the overall mission.

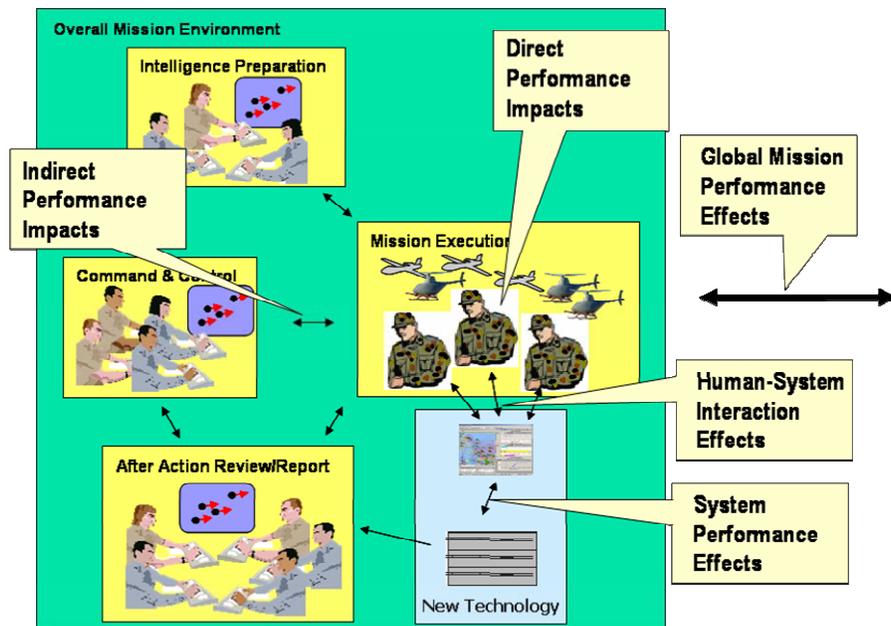


Figure 1. Measurement opportunities for evaluating new technology effects in complex mission environments.

An Example Technology

This paper describes the evaluation of SPEYES: a new set of technologies intended to enhance C3I performance in infantry soldier operations. SPEYES technologies include *sensing* technologies (Figure 2) – low cost, easily-emplaced, camouflaged sensors (video, acoustic, infrared, motion); technologies to support *situation awareness/command and control* – tools tailored for small unit operations (planning, blue force tracking, resource management); and *shaping* technologies, such as tools to detect vehicle-borne improvised explosive devices (Popp, 2005).



Figure 2 – An example of an unattended sensor

The SPEYES technology enablers are meant to increase the effectiveness of soldiers with improved threat detection and prediction, increased situational awareness, and improved decentralized operations. For example, the speed and ability of US forces to gather intelligence by the combined use and smart placement of visual, acoustic, and infrared sensors. The information gathered from these sensor observations are used by troops and commanders to gain improved situational awareness which facilitates resourceful patrolling. Efficient observations combined with more accurate and timely orientation is believed to lead to quicker, more effective actions.

The Evaluation Challenge

SPEYES technologies are expected to have direct impacts on command and control decision-making for infantry operations in urban environments, ultimately leading to improved mission performance in these environments. Hence, evaluating SPEYES requires the ability to measure command and control effects as well as mission performance effects for urban infantry operations across an array of missions with a wide range of variability. There are three general test environments that can be used to evaluate new technologies: 1) constructive simulations, 2) human-in-the-loop (HITL) simulations, and 3) field assessments (Figure 3). There are inherent tradeoffs between these environments for an evaluation effort such as SPEYES (Table 2). Because of these trade-offs, no one environment can address all the requirements for evaluation, and technology evaluation efforts increasingly are conducted in an iterative manner across several simulation and field test environments.

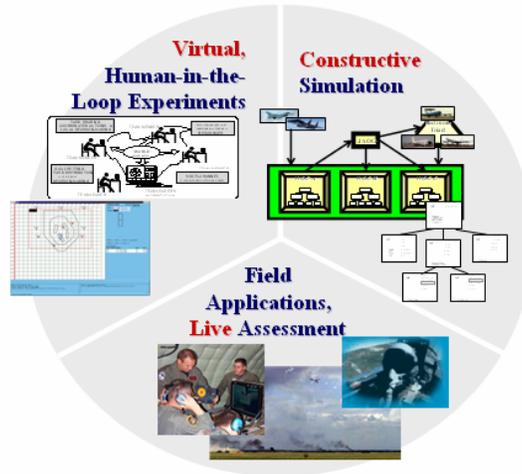


Figure 3 - Measuring technology insertion impacts

Table 2. Trade-offs between technology evaluation test environments

	Field Testing	Virtual Human-in-the-Loop	Constructive Simulation
Strengths	<ul style="list-style-type: none"> Valid results (Evaluations closely match operational environment) Great ability to observe complex human-system performance effects 	<ul style="list-style-type: none"> Some control over variables Some ability to observe human-system interaction Easier to collect measures Less expensive (after simulation is built) 	<ul style="list-style-type: none"> High degree of control over variables Easy to collect measures Inexpensive (after simulation is built) Easy to evaluate a wide range of missions and scenarios
Weaknesses	<ul style="list-style-type: none"> Limited control of variables Difficult to collect measures Expensive & limited by human SME availability (difficult to evaluate a wide range of scenarios and missions) Technology and training must be “field ready” 	<ul style="list-style-type: none"> Need to validate results in field environment Limited by human SME availability (difficult to evaluate a wide range of scenarios and missions) Need to train SME operators 	<ul style="list-style-type: none"> Need to validate results in field environment Cannot observe complex human-system interaction effects.

For SPEYES technology evaluation, the high expense, lack of field-ready technology, and variability of expected missions and scenarios made field testing an inappropriate solution. And while virtual (HITL) environments offered some improvements, it too had limited ability to handle the variability in expected missions and scenarios for SPEYES. Constructive simulation offered the most viable logistical solution, but it was critical for the constructive simulation to be able to provide measures of complex human-system

interaction effects for command and control and mission performance. The development of an agent-architecture for constructive simulation of command and control addressed this requirement.

Approach

Modeling and simulation can support experimental design, staffing, technology use, measurement, and can focus field studies on the most relevant parameters of a system. Fortunately, simulations can fulfill a key complementary role in the testing and evaluation of C2 technologies and associated TTPs before they are inserted in the field. By utilizing constructive simulations, we are able to test a multitude of alternative organizational structures, technologies, and decision-making models. Although there has been some work regarding the use of agent-based models for the evaluation of technology (Bonabeau et al., 2003; Wijesekera, D., 2005), less focus has been on the impact of these systems on performance and the overall effects of various trade-offs in technology and mission parameters.

Previously, human-in-the-loop and agent based experiments were conducted to test various concepts including organizational congruence, novel network-centric operations, strategy selection tradeoffs, and organizational adaptation (Kleinman et al., 2003; Diedrich et al., 2003; Entin et al., 2003; Levchuk et al., 2003). Both of these approaches – human-in-the-loop simulations for small-scale organizations, and synthetic agent simulations – have limitations. Large-scale experiments with human teams are expensive and time consuming. Thus, a very limited number are conducted, mainly testing incremental changes to the current doctrine rather than revolutionary ones. Current synthetic simulation environments capture only simplified aspects of human behavior, so their results are of dubious validity. We identified a need for low cost, highly valid constructive simulations of human operators and teams. These produce a significant gain in research impact by creating executable models of individual and team decision making that can replace human operators in organizations, and be validated against them.

To demonstrate and evaluate the effects of technology of C2, we developed computational models of distributed decision making, command, and control - which were used to simulate the processes of military C3I (e.g., decision-making and information processing) during mission execution. The models required a quantitative representation of military missions and the C2 organization. These missions and organizational structures were vetted with subject matter experts (SME) and representative of real world tasks. Next, we identified and represented the interactions required to execute those missions. Finally, the models were implemented within constructive and virtual simulation environments to conduct the experiments.

To address the goals of our research, we developed a flexible, controllable, distributed simulation/experimental paradigm suitable for examining the threats and mission essential tasks in urban environments and for quantifying the potential performance improvements of the SPEYES system over current practices. This simulation model captured many relevant key metrics and TTPs. The approach utilized the Dynamic

Distributed Decision-making (DDD) Environment as both a virtual and agent-based constructive simulation. This model addresses some key questions, such as:

- Mission Scenarios & Human Team/Organization
 - What tasks need to be accomplished?
 - What “players” are involved in the mission?
- Technologies Attributes
 - Who owns the technology (Soldier, Company, Platoon level)?
 - What can it do?
 - What functions can it perform?
 - What operators are needed?
- Translate into simulation variables
 - What are the capabilities of the technology we can model?
 - What are the effects of the technology for the model?
- Measures of performance and process
 - Which measures are applicable for both the field and simulation?

As field experimentation provides information on what to measure, such as information superiority, sustainability, mobility, training, and survivability; the DDD simulation provides the data for measurement. This results in interdependent measures such as latency, throughput, and resource utilization and influences dependencies on new technologies.

Dynamic Distributed Decision-making Environment (DDD)

The DDD (Kleinman et al., 1996) is a distributed real-time simulation environment implementing complex synthetic team tasks that include many of the behaviors at the core of almost any team mission: assessing the situation, planning response actions, gathering information, sharing and transferring information, allocating resources to accomplish tasks, coordinating actions, and sharing or transferring resources. Successive DDD generations have demonstrated the paradigm’s flexibility in reflecting different domains and scenarios to study realistic and complex team decision-making. The DDD is installed and used at more than twenty sites worldwide by researchers, trainers, and practitioners. It has already proven an effective test bed for conducting experiments in a number of different tactical environments including the Airborne Warning and Control System, Naval Battle Group, Army Ground Maneuvers, Army Urban Warfare/Special Operations, Search and Rescue, and Joint Peacekeeping Operations. Figure 4 shows the modeling process and examples of previous applications of the DDD.

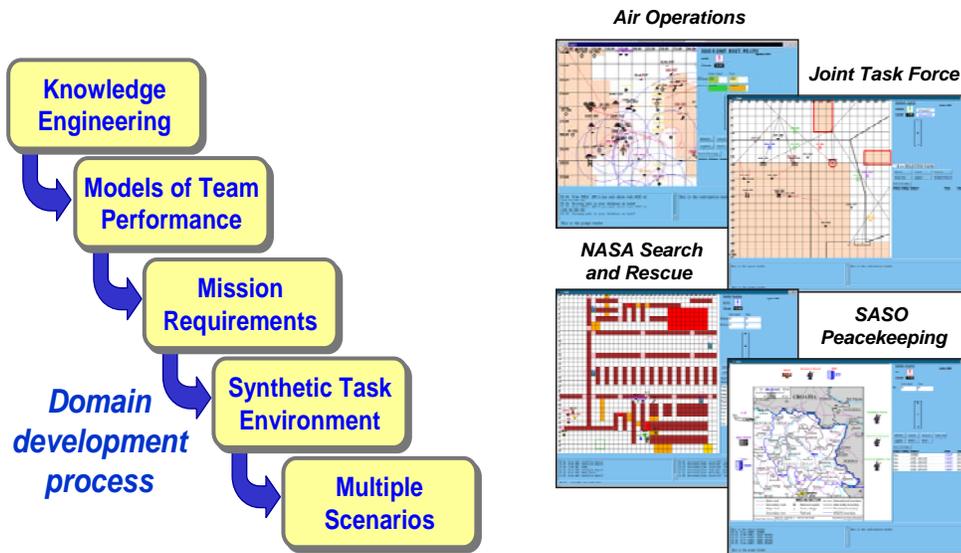


Figure 4 - DDD modeling process and previous applications of DDD

In general, the DDD provides an extensive set of capabilities for supporting team experiments. Although many multi-person wargaming simulators exist today, the DDD is unique in its *flexibility*. Most team simulators are built with a task, information, resource and command structure that replicates a specific military team task. The DDD, in contrast, was designed to capture the essential elements of many different C2 team tasks, and allow the experimenter to vary team structure, access to information, and control of resources. Because it is rooted in a strong C2 performance paradigm, the DDD has been able to provide a substantial degree of control, while engaging the team players in a low-to-moderate degree of realism, in very different environments. The reason the DDD simulator, more than any other team simulator, has been able to step “out of the curve” is because it infuses its team processes with a large degree of *functional* fidelity, by focusing on the team functions (e.g., communications, coordination, compensatory behaviors, hierarchical processes, etc.), as opposed to the *physical* fidelity that comes very often at the expense of precise control of variables. The gradual introduction of technology into the simulator (e.g., net protocols, multi-media displays, standard symbology, verbal and electronic communications, realistic force-on-force scenarios, active tactical maps, etc.) further increases the degree of realism without affecting the DDD’s ability to carefully manipulate a large set of external and internal team variables.

The DDD has successfully supported numerous virtual HITL experiments, but as discussed previously, HITL testing was not a viable solution for the SPEYES problem. However, the results from HITL testing provided a model for an agent-architecture that could enhance the DDD environment for more rigorous constructive simulation to evaluate technology its impact on C2.

Learning Complex Human-System Interaction from Virtual Simulations

In recent Adaptive Architectures for Command and Control (A2C2) experiments (Diedrich et al., 2003; Entin et al., 2003) we observed that human operators exercised several trade-offs between accuracy and timeliness of task execution to achieve higher mission effectiveness. The *task accuracy*, or effectiveness of task execution, is achieved by selecting the set of assets to execute a task to satisfy all of its resource requirements. The *timeliness* refers to how fast a task can be executed. However, due to resource shortage, not all of the most efficient resource allocation decisions can be performed in a timely manner (Levchuk et al., 2003). To execute tasks faster, operators may use fewer resources than required. Although this improves the timeliness of a tasks' completion, it reduces the execution accuracy (efficiency) of individual tasks. Another component of this problem is the cognitive limitations of the human operators who monitor and physically control resources. The timeliness of task execution depends on the ability of an operator to perform corresponding control functions – even when all resources are available for efficient task execution. Due to the constraints on cognitive workload, operators are faced with limits on communication as well as the number of resources they can control. These affordances must be weighed against the need for information sharing and inter-agent communication (required synchronizing actions and coordinating task execution). In essence, operators must account for how fast the communication, control, decision making, and observation activities associated with the resource allocation decision can be performed. Thus, human operators account for the efficiency/accuracy of the individual tasks' execution, the time when these tasks will be accomplished, and how much resource-task allocation decisions impact the future operation (activities/functions execution) of decision-makers. Since the task timeliness is affected by the ability of decision-makers to perform individual functions/processes, operators must take all of these processes into account. Previous computational frameworks modeled team coordination and individual asset control workloads (Levchuk et al., 2003). However, we observed that human operators employed different trade-offs under different organizational conditions (Entin et al., 2003; Diedrich et al., 2003; Kleinman et al., 2003). The insights from these HITL experimental results provide a model for representing human behaviors in the form of simulation-based agents.

Agent-based Modeling

Our computational model represents human operators as cooperative agents organized in a command and control structure. Individual agents make decisions that affect other team members, and the outcomes of those decisions are influenced by the position of agents in the organization (command structure) and access to resources (control structure). Agents communicate among each other to share information, submit requests, send orders to subordinates, and to synchronize the assets to facilitate task execution. Agents perform four main functions (also called *processes*): observation, communication, decision making, and resource control (Figure 5). The *observation function* is related to gaining situation understanding via observing the environment. This function depends on the responsibility of the corresponding commander (e.g., the commander needs to monitor the situation in a geographically constrained region, or is responsible for a function such

as anti-air warfare and therefore is monitoring air space). The observation process results in improved situation awareness for an agent and can provide information about what targets appeared or disappeared as well as individual and shared state. This can include the status of an agent's assets or the assets of other agents, the status of plans, mission tasks, and actions. The *communication function* allows the agent to communicate information, requests, and orders to other agents. The message traffic must be handled by a corresponding communication network. Communication is also needed to synchronize task execution by multiple assets which are controlled by different agents. The *decision function* allows the agent to reason about resource allocation and task assignment problems. These decisions are based on the situational representation that the agent has built from observations and information obtained from other agents. The decisions are constrained by the role of the agent in the organization, its position in command hierarchy (what subordinates the agent has), and its controlled resources/assets. Finally, the *control function* allows the agent to coordinate its assigned assets and resources to gather information, maneuver in the environment, execute tasks and engage the enemy.

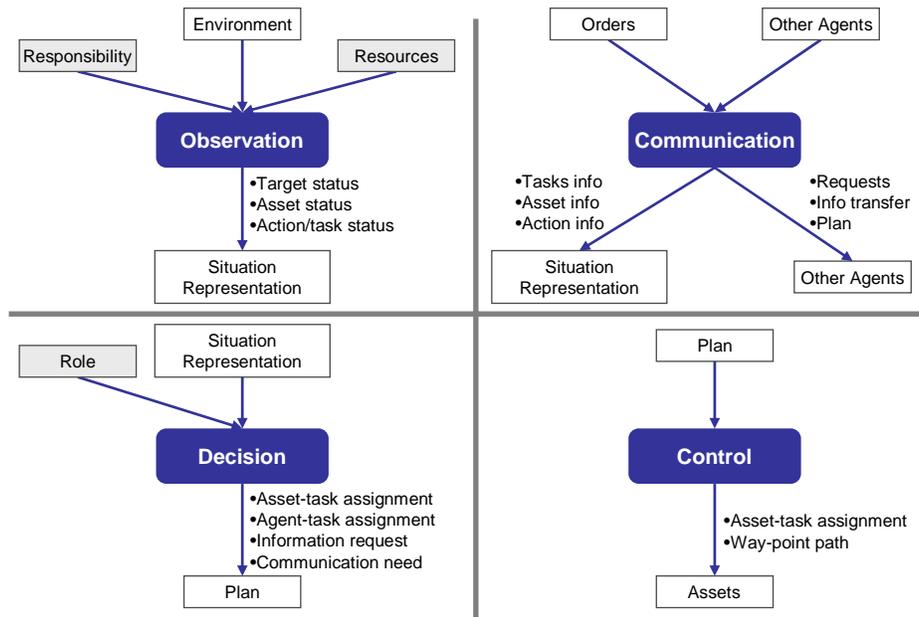


Figure 5 - Four main functions/processes of computational agent model

Analysis and Results

While innovative technologies and new operational concepts can present an individual multiplier effect, the goal of the SPEYES study was to explore and determine the impact and force multiplier payoffs that an integrated system of varied technologies might provide. To meet this objective, we aligned operationally relevant measures from field experiments to present a realistic assessment of the utility of the SPEYES technologies and to analyze new TTPs in order to determine the overall effectiveness on mission performance. This process is illustrated in Figure 6.

We conducted quick sensitivity and simulation analyses to assess the impact of the SPEYES system on the *efficiency* of C2 processes and the *effectiveness* of mission execution. Operational efficiency measures (measures of performance or MOP) focused on maintaining the same degree of force protection, while decreasing the number of personnel, amount of equipment, and cost/resources needed to sustain a particular level of protection. The measures of effectiveness (MOE) were defined by improved force protection and incident prevention. In addition to the evaluation of technology on C2, our integrated framework facilitates the assessment of the impact of key factors on individual workload, team processes, and mission effects.

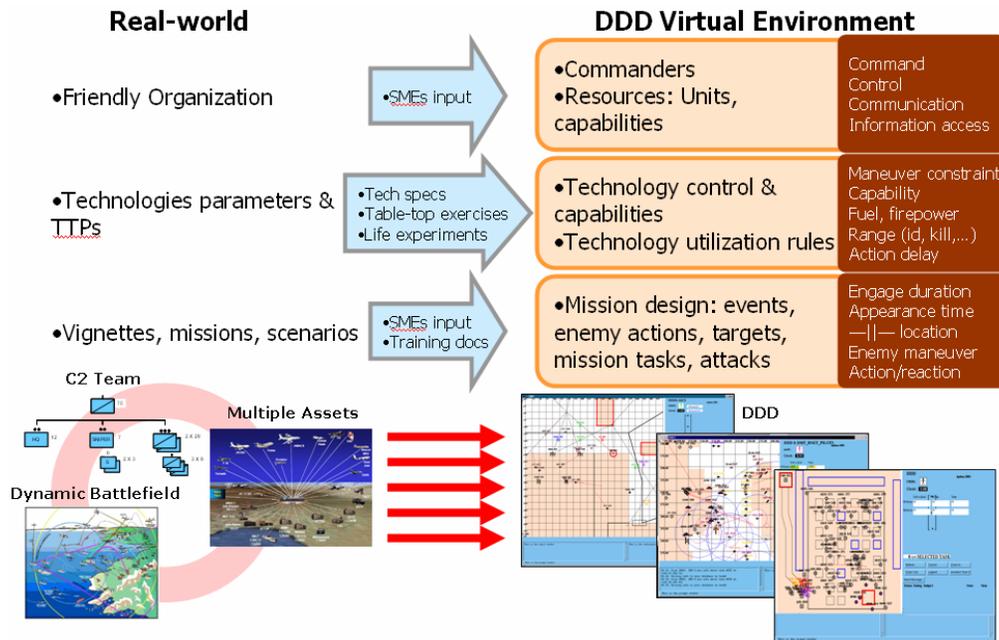


Figure 6 – SPEYES assessment using DDD

Several independent and dependent metrics from field experimentation and current military doctrine were identified for the evaluation of SPEYES technologies, which we aligned with field test metrics in order to validate the model. For example, the overall task processing throughput, which is the ratio of the number of tasks processed to the mission completion time, indicates the rate at which activities are accomplished by the friendly forces. A series of simulation experiments were executed for different packages of technologies, various scenarios, organizational structures, and technology utilization. These were defined by subject matter experts where technologies were thought to provide the most benefit. The scenarios included area reconnaissance, cordon and search, patrolling routes, and establishing observation posts. Various tasks of interest were identified including:

- Snipers and insurgents
- Re-entering a cleared building
- Reinforcement of cordon area from outside
- Communications to unit leader from inside buildings and across cordon areas

We also identified the top threats that could be encountered during these missions, such as improvised explosive devices (IEDs), rockets and mortars, snipers, vehicle born IEDs (VBIEDs), and small arms fire.

The results attained were promising and showed that the SPEYES system achieved force-multiplying payoffs using an array of integrated SA/C2 technologies. Specifically, technologies provided a significant reduction in mission completion time, substantial reductions in friendly casualties, large reductions in successful enemy sniper and RPG attacks, significant improvement in task throughput, and troop utilization efficiencies. These results suggest that improvements in manning, operational performance, and C2 can be achieved by integrating individual novel technologies into the SPEYES system. As part of the analysis, a variety of challenges were generated for the SPEYES system, for example:

- To what degree will surveillance technology improve the speed, security, and quality of searches?
- Will utilizing unattended sensors provide sufficient intelligence to allow troops to accomplish other tasks?

We hypothesized that using certain surveillance technologies would increase the speed of operation, and conducted experiments to confirm or refute these assumptions. Figure 7 shows an example of an *initial* result of an experiment from a simple version of the agents we developed, illustrating the improvement on the average time to search and secure buildings (immediate and second-order effects) with and without the SPEYES technologies (six building company-sized scenario).

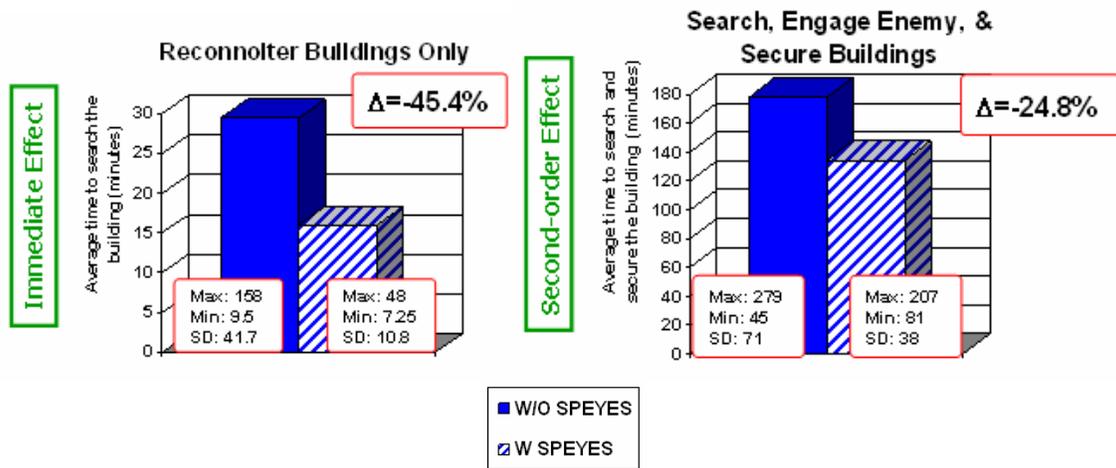


Figure 7 – Technology and speed effects

Although more experiments are needed for a complete analysis, the initial implications of this research impacted decisions to equip units in the Army for operations in Afghanistan and the Marines for operations in Iraq. This success demonstrates the potential utility of our approach to the evaluation of technology on C2.

Discussion and Conclusion

Our assessment methodology has been applied to evaluate the benefits of the SPEYES system – a ground-based, decentralized, multi-echelon C3I system comprised of emerging and existing Sensing, SA/C2, and Shaping technologies, and tailored for squad level, small unit forces. Historically, rapid post-conflict stability has been attained through high-troop densities. A key motivating theme leading to our research effort was the challenge of trying to enhance the effectiveness with a limited number of forces through various technologies. Accordingly, goals of the SPEYES experimentation included quantifying the force multiplying effect of SPEYES system, assessing its effects on mission performance, and evaluating the impact of technologies on C2. The performance improvements were measured in terms of timeliness, effectiveness, and efficiency of operations.

In this paper, we presented a computational framework and approach to assess the effectiveness and efficiency of C2 organizations and the impacts of advanced technologies. Our process draws on strengths of field assessment, virtual simulations, and agent-based constructive simulations. Agents are based on a quantitative representation of the organization, resources, mission, and utilization of normative models of team and individual decision-making in a C2 environment. One of the challenges in this work was developing representations of novel systems and technologies, some of which initially existed only as a concept. To facilitate the assessment, our models have been implemented within the DDD simulation environment. A major challenge of this work was to match the performance of synthetic decision-making (cognitive) agent models with real human C2 organization performance. We are currently implementing a more flexible agent paradigm that models technologies at a higher physical fidelity (sensor and dynamic models), and humans at a higher cognitive fidelity (workload and process based models, Levchuk et al., 2002; (Levchuk, Yu, Pattipati, and Levchuk, 2003), as shown in Figure 8.

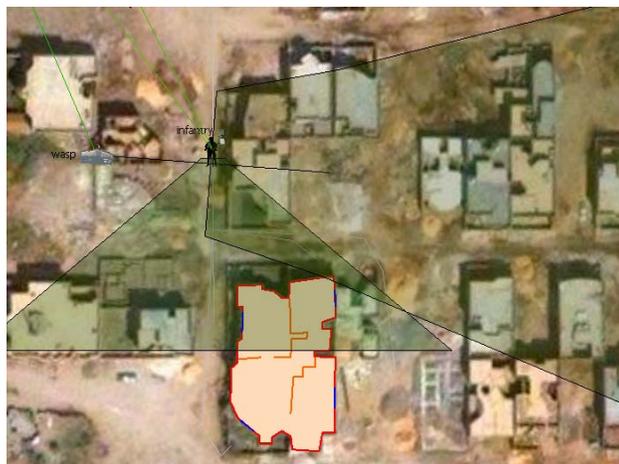


Figure 8 – Example of agent-based constructive model

The initial agent-driven simulation results indicated that integration of SPEYES sensing, SA/C2, and shaping technologies provided significant performance improvements to the

force across all measures. Even at 50%-reduced force, the SPEYES system maintained significant performance improvements over regular operations with a full force and without SPEYES, thus confirming the force multiplier effect of SPEYES technologies. Those findings were confirmed by human-in-the-loop simulations.

Throughout this paper, we have described the evaluation of technology as it applies to mission performance and C2. More generally, the evaluation of technology is becoming an increasingly important area for purchasing, funding, and engineering decisions. Table 3 illustrates how the results of SPEYES could be used to aid in the decision-making process. In addition, this framework could improve the ability to design decision support systems; facilitate important acquisition decisions concerning new systems; and help develop organizational designs, doctrine, and mission plans that exploit affordances in socio-technical systems in order to avoid pitfalls.

Table 3 – Technology evaluation for SPEYES

Purchasing and funding decisions	Engineering decisions
In terms of a viable solution, SPEYES agent-based simulations predict that the technologies can improve local mission performance.	In terms of performance objectives, SPEYES simulations provide baseline predictions of magnitude of performance improvements expected from these technologies.
	In terms of reliability, SPEYES simulations assess different tasks and missions, providing insight about circumstances that may challenge systems.

Acknowledgements

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