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MILITARY APPLICATIONS OF AGENT-BASED SIMULATIONS

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ABSTRACT

There continues to be increasing interest from a broad range of disciplines in agent-based and artificial life simulations. This includes the Department of Defense—which uses simulations heavily in its decision making process. Indeed, military conflicts can have many attributes that are consistent with complex adaptive systems—such as many entities interacting with some degree of autonomy, each of which is continually making decisions to satisfy a variety of sometimes conflicting objectives. In this paper, we present three applications of agent-based simulations used to analyze military problems. The first uses the MANA model to explore the ability of the U.S. Army's network-based Future Force to perform with degraded communications. The second studies how unmanned surface vehicles can be used in force protection missions with the Pythagoras model. The last example examines the standard Army squad size with an integrated effort using MANA, Pythagoras, and the high-resolution simulation JANUS.

1 INTRODUCTION

The Department of Defense (DoD) uses simulation models to enhance training and support decision-making. These models help test war plans against adversaries, influence force structure decisions, determine what equipment to acquire, decide the best combination and use of weapons, and explore potential changes in doctrine or tactics (Cioppa 2003). Since there are many factors that can potentially affect military conflicts, most of the traditional community simulations are extremely complex and resource intensive. The scenario generation process for these high-resolution simulations is man-hour intensive and requires detailed knowledge of the simulation models' underlying data and operating assumptions.

The time-intensive data collection/scenario generation process, coupled with long run times, often limits analysts to a small set of simulation runs. Unfortunately, in most defense studies there are substantial uncertainties that need to be addressed. For example, what forces could be involved in potential conflicts? Where, when, and how might these future battles occur? What equipment will be used? How well and reliable might the equipment perform? And, of course, how might the humans involved perform? Since some of these simulation inputs are unknowable, it makes sense to reason across a broad range of input variable levels (Bankes 1993). Otherwise, the analyst may obtain a limited view of the possible outcomes suggested by their model. However, as noted above, traditional, high-resolution DoD simulations lack the agility necessary to enable a broad exploration of the feasible input space. Consequently, their use alone may result in less-than-optimal recommendations being presented to senior decision makers.

To enhance our ability to broadly consider the uncertainties associated with potential conflicts, DoD analysts need tools and methods to explore a greater range of possible inputs and their associated outcomes before committing to an approach that will produce only a narrow scope of detailed results. An exploratory analysis approach—enabled by simulations, design-of-experiments methods, and high-performance computing—is one vehicle that may provide analysts with a broader and more robust range of potential insights. These insights may include, but are not limited to, exploring unintended consequences, identifying trade-offs in variables and constraints, enhancing the intuition about a scenario, and ultimately providing a good and robust solution despite the great uncertainty associated with warfare (Horne 1999). The exploratory approach can be utilized to decide how best to make use of high-resolution simulations, or to guide the overall effort for addressing questions not amenable to analysis using existing models.

We will show how agent-based simulations (ABSs) can provide a medium to utilize the exploratory analysis concept. In the following section, we briefly discuss ABSs, with an emphasis on why DoD analysts are interested in them. Section 3 provides an overview of an environment developed by Project Albert, a division in the Marine Corps Warfighting Laboratory (MCWL), for doing exploratory data analysis (also known as data-farming) with ABSs. Section 4 summarizes three diverse military applications using Project Albert's infrastructure (models, methods, and high-performance computing). Our conclusions and recommended research directions are contained in Section 5.

2 AGENT-BASED SIMULATIONS

There is no universal agreement on the precise definition of an agent-based simulation. In their most basic form, agents are software objects that perceive their environment through sensors and act on that environment (Weiss 1999). Agents may be able to communicate directly with other agents, are driven by a set of tendencies in the form of individual objectives or satisfactions, possess resources of their own, are capable of perceiving their environment, possess skills, and whose behavior tends towards satisfying its user-defined objectives (Ferber 1999). In short, an agent can sense their environment, communicate with other agents, build perceptions, make decisions, and take actions in an attempt to simultaneously satisfy multiple objectives.

ABSs are based on the idea that is possible to represent in computerized form the behavior of entities which are active in the world, and that it is thus possible to represent an emergent collective behavior that results from the interactions of an assembly of autonomous agents (Ferber 1999). Interesting and often unexpected emergent behaviors have been discovered in a diverse set of application areas. The list of working papers maintained by the Santa Fe Institute (2004) and the Center for Naval Analysis (2004) cover a wide range of topics in agents and complex systems; Sanchez and Lucas (2002) also provide an overview of recent ABS applications.

The natural progression of the agent is into a multi-agent system. This bottom-up modeling technique uses many diverse agents to imitate selected aspects of active components in a real world system (Weiss 1999). A further extension of the multi-agent system is the complex adaptive system. Complex adaptive systems can be regarded as being essentially open-ended problem solvers (Ilachinski 1997). The ability of complex adaptive systems to survive in a constantly changing environment is determined by their ability to find new strategies to survive.

Military combat has many of the key features of complex adaptive systems (Ilachinski 1997). Combat forces are composed of large numbers of nonlinearly interacting parts that are organized in a command and control hierarchy. However, each soldier on the battlefield has some degree of autonomy and is continually making decisions to satisfy a variety of sometimes conflicting objectives. For example, a soldier may simultaneously desire to move towards an objective, remain unobserved by the enemy, obey his commander's orders, stay close to his friends, etc. In addition, each of the soldiers in a unit may value the various objectives differently. Consequently, there may often appear to be disorder at the local level, but long-range order at the global level. Indeed, using very simple models, Ilachinski (1997) has observed "an impressive array of emergent behaviors," such as frontal assaults, retreats, guerrilla-like attacks, flanking maneuvers, encirclements, and many more.

ABS represents a shift from the traditional force-on-force attrition calculations (typically containing scripted entities or utilizing humans for decision-making) to considering how high-level properties and behaviors of a system emerge out of low-level rules applied to individual agents. The conceptual focus shifts from finding a mathematical description of an entire system to a low-level rule-based specification of the behavior of individual agents making up that system (Ilachinski 1997).

Aspects of ABS have been used by DoD analysts for years. The new concepts are the term agent and a few aspects of ABS—specifically the representation of knowledge and behavior. In addition, with ABS, there has been an emphasis on using simulations that are relatively low-resolution with respect to traditional models. The examples we will show below utilize simulations that attempt to capture only the salient features of the situation without trying to model all of the details that could be considered. Such simulations are sometimes referred to as distillations (Brandstein 1999).

3 AN ENVIRONMENT FOR EXPLORING AGENT-BASED SIMULATIONS

Project Albert is an ongoing MCWL research program whose genesis was a desire by senior Marine leadership to apply emerging technologies (such as complexity sciences and high-performance computing) to address some of their toughest analysis issues (Marine Corps Warfighting Laboratory 2004). In particular, Project Albert seeks to "explicitly represent and deal with nonlinearity, intangibles, and cooperative and competitive coevolution" (Horne 2001). A critical element in many studies in this area is exploratory analysis, or data-farming. The adaptive nature of ABSs makes them amenable to exploration. That is, agents adapt to the variety of conditions that occur over the broad set of inputs. Simulations with entities that have scripted decisions or utilize a narrowly tailored set of decision rules often enter regions where the agents make nonsensical choices.

With an exploratory approach in computer experiments, the focus is on helping explore the issues in a structured way to uncover new insights and reveal surprising characteristics. The goal then is to use models, designs, and analysis methods that can organize debates, efficiently uncover new insights, and effectively communicate the findings to decision makers (Hughes 1997). The exploratory analysis approach is an attempt to help people think through complicated issues by illuminating the consequences of various assumptions, reinforcing or challenging intuition, illustrating alternatives that might not have been considered, and generating questions that otherwise might have been overlooked. In short, the primary goal of this exploratory analysis is to gain a better understanding of the system, by identifying significant factors and interactions, as well as finding regions, ranges and thresholds where interesting things happen (Lucas et al. 2002, Kleijnen et al. 2004). This contrasts sharply with the traditional uses of simulations—predicting, optimizing, or tuning—as articulated by Sacks et al. (1989). In order to facilitate these types of analyses, Project Albert has developed and is continually enhancing an infrastructure that contains a suite of models, access to high-performance computing, readily available high-dimensional experimental designs, and analysis and visualization tools.

The simulation platforms in the Project Albert suite are, by design, easy to set up, quick-running, and suitable for data-farming. An experienced user can often build initial scenarios in hours to days, depending on the problem. Most of the scenarios are constructed so that they take only a few seconds or minutes to run on a personal computer. Furthermore, these models are resident at the Maui High-Performance Computing Center (MHPCC) and experiments can be submitted over the internet. The computational power at MHPCC enables analysts to generate many thousands or even millions of computational experiments in single day. We are thus better able to explore the vast space of possibilities suggested by the model.

With so many computational experiments feasible, the question remains: from the essentially infinite set of possibilities, what experiments should one take? The ability to conduct thousands of simulation experiments sounds like a lot, especially to those accustomed to running traditional DoD simulations, but in reality, this allows only a relatively sparse sample of the possibilities for high-dimensional explorations. Moreover, simply generating large volumes of data can easily overwhelm most post-processing analytic tools, leaving the analyst limited in their abilities to statistically interpret the results.

The exploratory analysis approach requires analysts to have experimental designs capable of efficiently searching an intricate simulation model that has a high-dimensional input space characterized by a complex response surface. To efficiently explore these simulation models, the experimental designs should have the following desirable characteristics:

- approximate orthogonality between inputs,
- space-filling behavior (i.e., design points are scattered throughout the experimental region with minimal unsampled regions),
- the ability to examine many variables (10 or more) efficiently,
- flexibility to allow for the estimation of many effects, interactions, thresholds, and other features of the response surface,
- minimal *a priori* assumptions on the response surface, and
- an easy method for generating the design.

The relationship between the quality and quantity of information and the resources required is one such that a gain in one causes (or requires) the other to increase (Cioppa 2003, Cioppa and Lucas 2004) The analyst must stay engaged in selecting and developing the appropriate designs. The analyst must determine which levels and configurations of variables to use and consider the effect on quality of information verses resources required.

Kleijnen et al. (2004) discuss situations where various classes of designs might be appropriate, but there is no one-fits-all design. However, in many of our explorations we want to screen many variables for importance while simultaneously maintaining the ability to fit complex metamodels to a handful of input variables that are found to have the most impact on the responses. Given this, and the above design goals, we have found specially constructed Latin hypercubes particularly useful in our explorations.

Once the data are generated, we need to extract as much information as possible. Once again, Project Albert provides useful resources with their visualization tool (Meyer and Johnson 2001). Combining the Project Albert visualization tool with standard statistics packages, both for graphics and model fitting, and interactively watching many scenarios unfold, has proven an effective means of generating insights. While a variety of analytical techniques have proven useful, we have gotten a lot of mileage from stepwise regression, non-parametric classification and regression trees, and multiple plots such as tiled contour and interaction plots.

4 APPLICATIONS TO DEFENSE PROBLEMS

In this section, we summarize three of the many ABS defense applications the authors have been involved with. These three examples are selected to illustrate the breadth of problems for which ABSs can be used effectively. The first example explores how communications factors affect a networked based system of many diverse agents' ability to conduct a company level attack operation. This study uses New Zealand's Defence Technology Agency's *Map Aware Non-Uniform Automata* (MANA) simulation platform). The second example applies MCWL's Pythagoras simulation to a study of a prototype Unmanned Surface Vehicle (USV) as a force protection asset. The last example integrates results from the MANA and Pythagoras models with the high-resolution simulation JANUS in a study of squad size.

4.1 Impact of Degraded Communications in the U.S. Army's Future Force

This subsection summarizes the research performed by Lindquist (2004) for the U.S. Army Training and Doctrine Command Analysis Center (TRAC) under the guidance of the authors. Captain Lindquist was asked to help quickly provide insights into the possible effects of degraded communications on the Future Force the U.S. Army is designing. While physics-based, high-resolution simulation studies are currently in process, these simulations lack the agility to look rapidly across a breadth of possibilities. Thus, the ability to focus experimentation efforts involving those high-resolution experiments is critical.

In a response to the rapidly changing threat and the revolution in information technologies, the U.S. Army is currently undergoing its most comprehensive transformation in over a generation. This transformation is characterized by a lighter, network enabled force. The new forces must be able to deploy faster, seize the initiative, and finish decisively. The centerpiece of the Army's Future Force is the Future Combat System (FCS) Family of Systems (FoS). The FCS utilizes advances in battlefield sensing, networks, and lethality to allow the battlefield commander to engage the enemy at standoff.

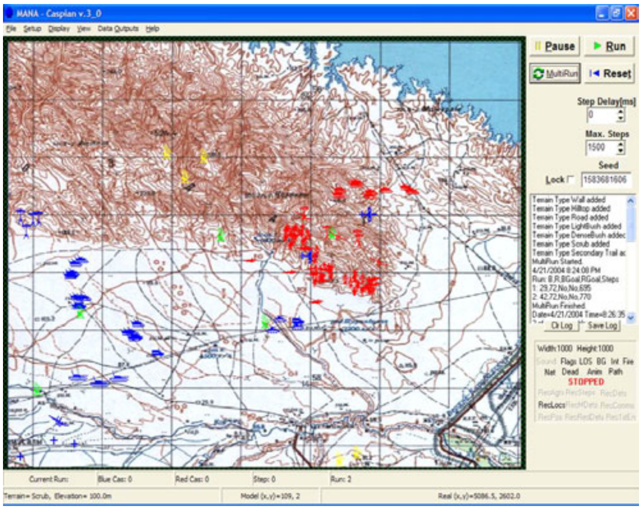
The system of systems that composes the FCS contains a mix of many diverse hunter and killers systems—all working together (U.S. Army 2003). This cooperation is predicated on sufficiently capable and reliable communications. How will the FCS's abilities be affected if the required communications capabilities are not there? This could occur either if the underlying technologies do not mature as fast as expected, or if the enemy uses countermeasures (such as jamming) to inhibit our communications during operations.

To ensure that the results of this analysis would be germane to the broader research effort, an existing TRAC scenario was used. The scenario had previously been analyzed by TRAC White Sands Missile Range on a physics-based simulation called JANUS. At the time, this physics-based simulation did not take the effects of degraded communications into account—though they have incorporated this feature in the last six months. The results below are all in the context of a Unit of Action Combined Arms Battalion in the attack using the Caspian Sea area of operations. The attack is against a prepared and well-fortified enemy in mountainous terrain above an airfield. Blue's objective is to secure the use of this airfield to facilitate freedom of maneuver of follow-on forces. We assume that Red forces have intelligence that indicates this desire, but are unaware of the time or precise location of the advance. Given this situation, Red arrays its forces in a decentralized area defense, occupying covered and concealed positions overlooking the airfield and its air corridors.

To uncover insights on the affects of degraded communications, MANA was used to explore the Caspian Sea scenario. MANA was chosen because it facilitates quickly constructing and exploring new scenarios. Its graphical user interface helps in building scenarios and the playback features are invaluable as an analysis tool. MANA allows considerable flexibility in creating a diverse set of agents. MANA entities maintain a memory of the battlefield (i.e., they are "map aware") and their behaviors can be built to change in response to a variety of battlefield events—such as being shot at. This simulation platform has been used in several previous studies, and thus, a set of existing object definitions exists for the systems of interest. Moreover, MANA is resident at MHPCC, and a process exists to readily enable an exploratory analysis. That is, Project Albert has software to automatically run a set of user designed MANA experiments based on state-of-the-art high-dimensional designs.

Once the scenario was selected, there remained the task of defining agents to represent the systems being simulated. In keeping with the spirit of a distillation, many of the agent's attributes (e.g., sensing ability, weapon's ranges and lethality, etc.) were defined by low resolution algorithms. For example, the detection used a cookie-cutter algorithm modified by line-of-sight calculations and parameters for concealment and stealth. In addition, since the focus of this analysis was on the communications aspects of combat, personalities (as defined by movement propensities) were only roughly modeled. Nonetheless, where possible, physical values (such as the rate of fire, maximum range, maximum speed, etc., were calibrated to the operational requirements document.

A screenshot of the baseline MANA scenario (taken from Lindquist 2004) is provided in Figure 1.



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Max. Steps 1500
Seed 1583681606
Lock

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Terrain Type Hilltop added
Terrain Type Road added
Terrain Type LightBush added
Terrain Type DenseBush addec
Terrain Type Scrub added
Terrain Type Secondary Trail ac
MultiRun Started.
4/21/2004 8:24:08 PM
Run: B,R,BGoal,RGoal,Steps
1: 29,72,No,No,695
2: 42,72,No,No,770
MultiRun Finished.
Date=4/21/2004 Time=8:26:35

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Current Run:   Blue Cas: 0   Red Cas: 0   Step: 0   Run: 2
Terrain= Scrub, Elevation= 100.0m   Model (x,y)=109, 2   Real (x,y)=5086.5, 2602.0
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Figure 1: Screenshot of the Baseline MANA Scenario

Agents in MANA build their perceptions through either their own sensors or over the network. The network is critical in this setting since many of the FCS's most lethal weapons will never see the target themselves. MANA does not explicitly propagate electronic transmissions through the environment or model the detailed electronics and signal processing associated with communications equipment. Rather, it lets the user define which entities are linked together and provides parameters to vary each node or link's capacity, latency, maximum range, queue buffer size, reliability, accuracy, maximum age, and delivery protocol (Lindquist 2004). Our interest was exploring how these factors affect our output measures and how this relationship depends on other critical parameters (e.g., the enemy's will to fight, when the Blue force employs its dismounts, etc.). The two primary measures of effectiveness in this exploration were the length of battle and the Blue (attacking FCS force) casualties. The simulation ended when the defending Red force took sufficient casualty so that it was no longer an effective fighting force.

All of the modeling in this study was done through the input variables—that is, no changes were made to MANA's code. As with most simulation development, there were some things that could not be explicitly modeled. For example, the physics behind the effects of the enemy's jamming was not explicitly simulated. To implicitly model the effects of noise jamming, Lindquist (2004) created fictitious communication nodes through which all Blue forces communicated. Each Blue agent is able to talk through two nodes—one of which captures the communication equipment's inherent capabilities while not under jamming, and another which captures the communication equipment's capability when under jamming. Each of these nodes follows the agents during movement—remaining invisible to the Red force and not affecting the Blue force other than in their role in passing information between agents. When an agent desires to communicate, it will do so through one of the two nodes. If the transmission is not jammed, the "inherent capabilities" node is used. However, when the enemy jams an agent its preferred communications node "runs away" and can't be used, so the agent is forced to use its less capable communications node. This modeling mechanism allowed a variety of levels of communication degradation to be explored.

Using combinations of factorial experiments and Cioppa's (2003) nearly orthogonal Latin hypercubes, more than 50,000 individual simulations were run and analyzed over nearly a score of variables. The key findings of Lindquist's (2004) analysis are the following:

- The communications factor that the responses are most sensitive too, over the ranges examined, is communication range. A degradation of 25 percent on the ability to communicate over the entire battlespace had dramatic, negative consequences for the Future Force.
- An unresponsive or slow network is nearly as detrimental to the FCS as diminished communications range. When intelligence on a fairly static enemy employed in the defense is delayed, the length of battle is extended and Blue forces generally pay for that delay in casualties.

These findings are summarized graphically in the regression tree of Figure 2. We have found these displays useful for succinctly presenting the results to decision-makers. The green, yellow, and red boxes at the bottom of the leaves correspond to favorable, intermediate, and unfavorable outcomes for Blue forces, respectively. The graph has been simplified from the statistical software output, which also provides the number of data points in each leaf (cluster), as well as their mean and standard deviation.

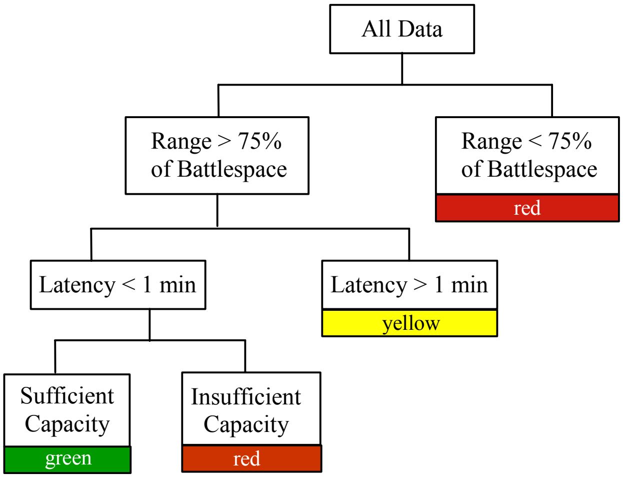

Figure 2: Regression Tree for Blue Casualties

Additional findings include:

- Reliability, while important, is not as significant in a system with many means of redundancy (such as the FCS). Even if a substantial amount of communication links are unable to relay enemy intelligence, there are many others that are able to "pick up the slack."
- Even a limited enemy electronic attack focused on a particular battlefield operating system can be effective. In this scenario the most lucrative target for the enemy is the Blue armor—the reason being that these systems are "in the front" and act as both hunters and killers.
- The lethality of the non-line of sight systems set the tone for FCS battlefield success and must be allowed to attrite the enemy as long as possible.
- Even with the technologically advanced Future Force, traditional determinants of battle outcome (leadership, enemy posture, friendly and enemy morale) are still important determinants of victory in this simulation.

A more thorough treatment of this investigation can be found in Lindquist (2004).

4.2 Unmanned Surface Vehicles

This subsection summarizes the research performed by Steele (2004) under the guidance of the authors. The Navy is considering the use of unmanned surface vehicles (USVs) to reduce risk to personnel in maritime interdiction operations, and to conduct intelligence, surveillance and reconnaissance (ISR) and force protection (FP) missions. An attack on 24 April 2004 against Sailors in a Rigid Hull Inflatable Boat (RHIB) illustrates why unmanned vehicles are being considered as a force in the fleet. During maritime interdiction operations in the Arabian Gulf, a 7-member crew RHIB proceeded to intercept and board an unidentified dhow for investigation. As the RHIB approached the dhow, it exploded—killing two Sailors and wounding four others. Two other unidentified dhows also exploded the same day (Navy Newsstand 2004). Ideally, USVs might help prevent the death and injury of Sailors.

The Spartan Scout is a prototype USV that deployed with the USS GETTYSBURG in December 2003. Essentially a 7-meter RHIB that has been configured for ISR, the current USV contains an electro-optical/infrared (EO/IR) camera, commercial grade radar, microphone and a loudspeaker. It is radio controlled with a current range of five nautical miles (nm) from the host ship. The USV is gas-powered with a projected endurance of six hours and a 10-foot height of eye.

Using the USV for surveillance could enable the host ship to detect and identify other objects on the seas that are outside of the host ship's visual and radar range. Interception (i.e., the ability to move towards the potential threatening contact) is a mission-essential task for maritime interdiction operations. The combination of surveillance and maritime interdiction capabilities expected from the USV may allow the Navy to perform these missions while the host ship continues on operational tasking and maintains its position. Another need for the USV is Force Protection (FP), as evidenced by the April 2004 attack. The host platform can allocate its resources in different ways to ensure proper defense.

Field tests involving the Spartan Scout's ISR capabilities took place in December 1-2, 2003 and January 19-22, 2004. However, the Navy has only recently begun to procure USVs, and it has not yet developed operational procedures for these assets. Determining how to configure and deploy the USVs to improve fleet operations is desirable, but the possibilities for gaining insights are limited when only a single prototype is available. Instead, we use agent-based simulation to examine configurations of the USV, the environment in which it operates, and various tactics for deployment. The goal is to take a first step toward assessing the benefits and shortcomings of adding USVs to the fleet. If performance estimates can provide information and insights to assist decision makers (or lead to further research involving specific areas of interest, tactical applications, or operational scenarios), that would also be a benefit.

This study uses an agent-based simulating platform Pythagoras to model the performance of the USV with respect to its current capabilities. The models are able to capture the way USVs act under a variety of circumstances. Factors of interest include those involving the operating environment (e.g., number of contacts, threat density, traffic patterns, sea state), tactical employment factors (e.g., planned or dynamic control, stationing, force protection tasking), and programmatic issues (e.g., number of USVs available, platform endurance, speed, camera range, etc.). We consider these for both the ISR and FP missions.

In Pythagoras, the agents autonomously sense and react to the operational environment using "soft" rules. This may allow the models to do a better job of mimicking the sometimes chaotic nature of combat than a model with "hard" rules. For example, for a rule to "shoot when the enemy is close," what constitutes "close" will differ from agent to agent and instance to instance. Another characteristic of particular interest for our study is Pythagoras' ability to model sensors and detection probabilities, allowing us to mimic the USV camera (or sensor) operating in different sea states.

Nearly orthogonal Latin hypercube designs (Cioppa 2003) were the basis of the experiment, although the limited number of levels for some factors (such as sea state) meant rounding was required. In all, over 380,000 experiments were run to obtain multiple replications at each combination of factor levels. One desired outcome of this work is to see if the factors examined yield evidence whether the USV is an appropriate solution to the tactical problem. We anticipate that we can provide some useful insights to the Navy by varying many factors across several operational scenarios, but it is optimistic to expect this study to enable the necessary decisions for full implementation of the USV into the fleet.

Three separate operational scenarios were modeled using the Pythagoras platform: an ISR mission with a pre-planned patrol pattern, and ISR mission with an interceptor model, and a Force Protection mission where enemy agents could swarm to attack the host ship. In all scenarios, contacts must be classified as threatening (i.e., enemy agents) or non-threatening (i.e., neutral agents). For modeling simplicity, agents were tagged as "killed" once they had been successfully identified.

Steele (2004) found that multiple regression models provided good fits to both the waypoint and interceptor ISR results. Relatively simple models account for over 85% of the variability in the proportion of enemies detected. The models included some quadratic and interaction terms, underscoring the need for assessing the factors' impacts in a single experiment, but presenting challenges for the system design. Figure 3 is an interaction plot for the Interceptor scenario. The tiny sub-plots depict the four significant interactions involving USV speed, combat radius, sensor range, and endurance. (Curves indicate quadratic effects.) For example, the top row shows that with a USV speed of 2 knots, increasing the sensor range has a slight negative effect on performance. In contrast, when the USV speed is 40 knots, then increasing the camera range is quite beneficial.

Closer looks at the joint effects of two factors are possible using contour plots. Figure 4 is such a plot as a func-

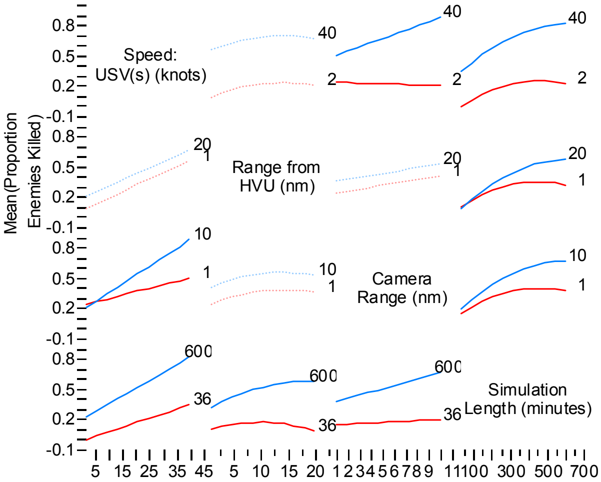

Figure 3: Interaction Plot for the Interceptor Model

tion of the USV speed and endurance. The darker red areas to the upper right represent high detection proportions, while the left and lower portions of the plot correspond to low detection probabilities. If either USV speed or USV endurance are low, then so is the detection probability. Improving only one will not appreciably improve performance. To achieve reasonable detection probabilities, both speed and endurance must be sufficiently high. This is but one instance of a situation where “more” is not necessarily “better.” Both ISR models revealed this behavior for more than one factor. For example, increasing the number of USVs from one to several is quite beneficial, but eventually having more does not improve detection capabilities. Knowledge of this type of diminishing return is important. The Navy program managers must make trade-offs related to cost and space utilization when they decide how many USVs (and with what capabilities) to procure.

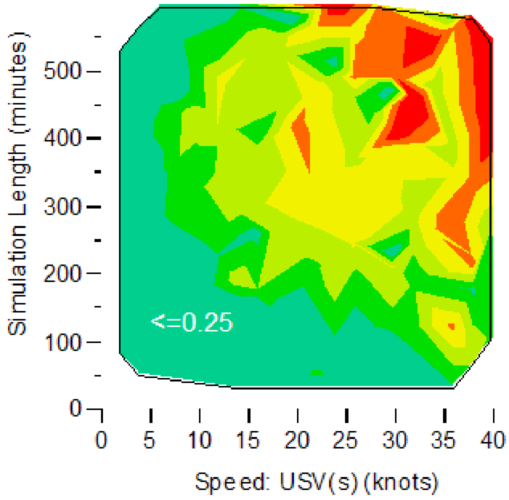

Figure 4: Contour Plot for the Interceptor Model

Two additional MOEs were considered for the Force Protection model: the proportion of threatening enemy agents detected, and the number that reach the high-value unit from which the USVs are deployed. The nonlinearities in all three MOEs meant that adequate regression models could not be constructed. Instead, we used regression trees to capture insights. For example, if the threat density (proportion of contacts that are enemies) is high, then the USV needs to go fast. If it cannot, then several USVs are needed to identify and intercept a fairly high proportion of the contacts.

Though only a first step, this work has both tactical and programmatic implications. Building the simulation models forces tactical thought. The ability to leverage the models by looking broadly across the factor space can help focus future field test efforts. Findings regarding the combined impact of sensor range, endurance, and combat radius can help inform program managers as the procurement stage progresses. Finally, tactics matter—better technology alone will not assure success.

A more thorough treatment of this investigation can be found in Steele (2004). As a direct link to disseminate information for the benefit of USV researchers and supporters, the results are being incorporated into a U.S. Navy Tactical Memorandum.

4.3 Squad-Size Exploration

The squad size experiment was developed with guidance from the U.S. Army Soldier Battle Lab’s Chief of Analytical Simulations in Fort Benning, Georgia. The impetus for the experiment was the ability to address a current and relevant Army issue in the Future Force and Future Combat System (FCS) Analysis of Alternatives (AoA) experimentation with a relatively new and emerging set of analytical tools. The experiment had two primary objectives. The first objective was to provide the Soldier Battle Lab with some potential insights and conclusions on the issue of reducing the standard Army infantry squad from 12 soldiers to 9 soldiers. The second objective was to provide a test case on the appropriateness of using these types of ABSs and experimental designs in an exploratory manner as a precursor to executing high-resolution simulation models. The ultimate goal is to reduce the resources required on the analyst and tasked organization, while increasing the quality of information that can be presented to senior decision makers.

We wanted to exploit advances in computing power and analytic tools, as well as look at the questions from a broad perspective, so we used a series of models and analytic tools in our investigation. We also wanted to utilize the current experimental design research so that the results of the simulation runs could be unraveled with a degree of statistical rigor necessary to determine significant factors and significant interactions. Two ABSs from the Project Albert family of models were used, Pythagoras and

MANA. The results from these explorations were used to design much smaller experiments involving the high-resolution simulation JANUS, allowing us to compare and contrast the results obtained by the three models. All three sets of experiments utilized nearly orthogonal Latin hypercubes (Cioppa 2003).

The basic distillation designed in Pythagoras represented a small urban area with a small number of structures. The Blue squad size was varied using 7, 9, and 12 agents per squad, and either 2, 3, or 4 squads were deployed in the urban environment. The squads were assigned a FCS vehicle representative of the future Armed Robotic Vehicle (ARV) concept. The Red agents comprised 4 groups of 36 agents and maneuvered throughout the urban environment. The Blue forces were directed to maneuver through the urban environment to a designated objective. The Blue squad's size, number of squads, and weapons, as well as the ARV's sensors and weapons mix were varied in the experimental designs. The measures of effectiveness (MOEs) were loss exchange ratio (LER) and time to mission completion. The focus for this experiment was on the physical characteristics of the agents such as numbers of agents, weapons, or sensor ranges. The aspect of human behavior was not explored.

The distillation was migrated across two agent based simulation platforms, Pythagoras and MANA, and finally to a third high resolution simulation model, JANUS. The scenario migration was a manual process, and minor changes were necessary at each step due to the different underlying operating assumptions of each simulation model. However, the intent was to keep the distillation as consistent as possible throughout the migration process and across the three simulation models.

The experimental design for a 16 factor, 65 run design was executed in Pythagoras, with 50 replications per input combination. We conducted a preliminary analysis of the output data, and gleaned the significant factors and interactions. A similar set of 16 factors was selected and a 16 factor, 65 run design, again with 50 replications, was executed in MANA and the output data collected and preliminary analysis conducted. The significant factors and interactions were also determined and compared with the Pythagoras output. Initial observations indicate minor differences occurred in the strength or level significance of certain factors and interactions, but the analysis indicated no serious inconsistency in the output of the two simulation models. The execution of the two agent based simulations and subsequent analysis provided insight into the factors selected for the high-resolution model, JANUS. Those factors in the agent based simulations that exposed regions of interest were then correlated to similar factors in JANUS. The decision was made to focus on a set of 7 factors in JANUS that potentially would lead to regions of interest. A 7 factor, 17 run design with 10 replications per run was conducted and the output was analyzed.

Table 1 provides a comparison among the results for the two agent based simulations (MANA and Pythagoras) and the high resolution simulation JANUS. The strong similarities among the three diverse simulations indicate a strong potential for gathering insights—and ultimately stating conclusions on the issues of squad size, number of squads, and ARV operations in an urban environment.

Table 1: Model Comparison for Squad Size Study

	MANA	Pythagoras	JANUS
Squad Size	S	M	M
Number of Squads	S	M	M
ARV Armor Thickness	M	N/A	S
ARV Speed	S	S	S
ARV Weapon Max Range	S	S	S
Weapon Max Ranges & Squad Firing Rates	S	S	N/A
Weapon Max Ranges	NS	S	S
Squad Firing Rates & Squad Size	NS	S	N/A
Number of Squads & Squad Firing Rates	NS	S	N/A
Scheme of Maneuver	N/A	N/A	S

M = Most Significant, S = Significant,
NS = Not Significant, NA = Not Applicable

We identified several regions of interest that merited more detailed analysis, particularly in relation to the squad size. The survivability of agents with squad sizes of 9 and 12 appears to be correlated with the survivability of the ARV asset. Essentially, it seems that that as long as the ARV survives, the differences in LER between 9 and 12 agents per squad are small. However, a significant change to the survivability of the Blue squads of size 9 occurs when the ARV is destroyed. This is consistent across all three of the simulations' output data.

Other interesting effects reflected in the loss exchange ratios involve interactions among the ARV speed, Blue squad size, and number of squads. The results indicate that as the ARV speed begins to degrade, then its ability to adequately support the squads with its increased technological capabilities also starts to degrade. Therefore, the concept of employment may need to be investigated further if the ARV cannot meet performance specifications.

After conclusion of this work for the U.S. Army Soldier Battle Lab, TRAC continued its exploration of agent-based simulations. For the FCS Key Performance Parameter study, TRAC identified an initial set of manned systems that were deemed most likely to experience some reduction in stated design performance. The six systems identified were incorporated into a design matrix (approximately 64 excursions) to examine the impact if some or all of these systems operated at a "minimum" capability. TRAC developed a scenario in MANA in order to provide insights and assist in reducing the initial design matrix to a viable set of five to eight excursions for execution in a high-resolution simulation.

Applying the exploratory analysis concept with the stated experimental designs provided a means of efficiently searching an intricate simulation model that has a high-dimensional input space characterized by a complicated response surface (Cioppa 2003). This exploratory analysis, followed by high-resolution simulation runs, proved to be an effective methodology.

5 SUMMARY

One need not look too hard to see similarities between many features of warfare and key aspects of ABS. Simple ABSs have already proven useful in generating insights and focusing high-resolution simulation experiments. For both of these purposes, the utility of ABSs is enhanced by an infrastructure that allows analysts to quickly build, run, and analyze many thousands of simulation experiments.

In this paper we have shown three diverse applications of ABSs to military problems, and could have shown a dozen more. Work is underway that could further improve the ability to leverage ABSs to help military decision makers. This includes the development and implementation of automated adaptive search methods, the creation of libraries containing accredited data for many systems and scenarios, and the enhancement of links between ABS and high-resolution simulations.

Design generators, links to the theses described in this paper, and links to several other related resources and research investigations are available from the authors or online (SeedLab 2004).

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