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DEFENSE AND HOMELAND SECURITY APPLICATIONS OF MULTI-AGENT SIMULATIONS

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ABSTRACT

Department of Defense and Homeland Security analysts are increasingly using multi-agent simulation (MAS) to examine national security issues. This paper summarizes three MAS national security studies conducted at the Naval Postgraduate School. The first example explores equipment and employment options for protecting critical infrastructure. The second case considers non-lethal weapons within the spectrum of force-protection options in a martitime environment. The final application investigates emergency (police, fire, and medical) responses to an urban terrorist attack. There are many potentially influential factors and many sources of uncertainty associated with each of these simulated scenarios. Thus, efficient experimental designs and computing clusters are used to enable us to explore many thousands of computational experiments, while simultaneously varying many factors. The results illustrate how MAS experiments can provide valuable insights into defense and homeland security operations.

1 INTRODUCTION

For many decades, Department of Defense (DoD) and other national defense analysts have studied potential large-scale warfare between states. The results of these analyses often inform decisions on how nations should build, organize, maintain, and, if necessary, employ their military and security forces. Since there is a dearth of such conflicts, most of this analysis has been and is being done via experimentation. Because of the expense and other constraints associated with live experimentation, much of this experimentation is done with simulation.

The simulations that have traditionally been used to examine large-scale, force-on-force conflicts are typically very large and are often tightly structured. The simulation size follows from the sheer number of entities involved and the extent of the conflicts being simulated. The structure follows from the forces' hierarchical organizations and carefully planned doctrine. Moreover, simulating human decision making is notoriously difficult, and is often done with humans in-the-loop or using subject matter experts to specify (or "script") behaviors.

Recent events have forced a change in emphasis of the situations that DoD and the Department of Homeland Security (DHS) study. Today's adversaries typically operate in small, decentralized, adaptive cells. The individual battles themselves usually involve relatively few combatants and are of short duration. These situations lend themselves to being examined with multi-agent simulation (MAS). Computational experiments using MAS allow insight into the relationships among various agents and their potential strategies and actions (Lucas and Sanchez 2002; Sanchez and Lucas 2002; Cioppa, Lucas, and Sanchez 2004). This paper extends earlier work, but shifts the application emphasis from force effectiveness to counter terror operations and employs more complicated (and bigger) experimental designs.

In its basic form, a MAS contains agents (i.e., software objects) that interact with each other and their perceived virtual environment. The hallmark of these models is the degree of autonomy of the individual agents. That is, the agents have a set of desires (e.g., stay alive, complete the mission, obey orders, move away from danger, etc.) and they take actions in an attempt to simultaneously satisfy multiple objectives. Interesting and unexpected macro behavior often

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emerges from these individual or micro actions (Illachinski 1997).

Another attractive feature of many of the MAS being used in defense and homeland security analysis is that they are relatively easy to construct and run quickly—at least in comparison to traditional DoD simulations. This, and their inherent flexible nature (i.e., the agents adapt to changing conditions), allows them to be used to quickly explore a wide range of possibilities. This is particularly useful in fluid situations involving a large number of uncertainties—as with many homeland security issues.

Most of the simulation models used in defense and homeland security analysis have a large number of potential input variables. Furthermore, the situations being modeled make it difficult to estimate the veracity of the models (Hodges and Dewar 1992). Such models are often best used for exploratory analysis. The exploratory analysis approach helps 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 would have been overlooked. In short, the primary goal of exploratory analysis is to gain a better understanding of the system or process 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. 2005). This contrasts sharply with the traditional uses of simulations—predicting, optimizing, or tuning—as articulated by Sacks et al. (1989).

Section 2 contains an overview of the tools and techniques for performing large-scale simulation experiments at the Naval Postgraduate School. This is followed by summaries of three recent thesis projects by SEED Center graduate students. Section 3 describes a study that examines the defense of thousands of simulated attacks on off-shore oil facilities. Section 4 reviews an analysis of how non-lethal weapons can be used to provide additional protection to ships in a crowded maritime environment. The last example, Section 5, examines the emergency response to a coordinated terrorist attack (consisting of a bomb and snipers) during a festival within a major urban area. Our conclusions and research directions are contained in Section 6.

2 EXPLORING MULTI-AGENT SIMULATIONS IN THE SEED CENTER FOR DATA FARMING

The MAS applications discussed in this paper are a few of those being used to explore national security issues by the SEED Center for Data Farming at the Naval Postgraduate School (NPS). *SEED* is an acronym for Simulation Experiments and Efficient Design, while *data farming* refers to using high-performance computation to grow data.

The SEED Center for Data Farming was established to advance the collaborative development and use of simulation experiments and efficient designs to provide decision makers with timely insights on complex systems and operations. The harvested data can then be analyzed using data mining and other statistical techniques. To achieve its goals, the SEED Center is building an environment that facilitates quickly building models; running them efficiently a large number of times over many input combinations; analyzing the output; subjecting the results to subject matter expert review; and iterating this process. The environment consists of several components:

- A family of tools for quickly constructing (mostly multi-agent) simulations. The examples in the paper use two such tools: (i) Map Aware Non-Uniform Automata (MANA), developed by New Zealand's Defence Technology Agency (Galligan, Anderson, and Lauren 2004); and (ii) PYTHAGORAS, developed by the Northrop Grumman Corporation (Bitinas, Henscheid, and Middleton 2006).
- A portfolio of experimental designs for use in model exploration. Simulation experimenters have a breadth of different needs, depending on the number of factors they wish to explore, the objectives of that exploration, the meta-models they desire to be able to fit, the run time required, and more. The SEED Center is continually expanding and improving on the collection of designs available for high-dimensional exploration, such as sequential screening (Sanchez, Wan and Lucas 2005, 2007), very large fractional factorial and central composite designs (Sanchez and Sanchez 2005), and specially constructed nearly orthogonal and space-filling Latin hypercubes (Cioppa and Lucas 2007).
- Computing clusters, which enable parallel execution of multiple computational experiments.
- Statistical analysis and visualization packages for gleaning insights from the output data.

While these components are necessary for our explorations, they are insufficient. Another key research direction of the SEED Center is the software that links these capabilities together to create an environment that allows modelers, analysts, and subject matter experts to quickly construct and analyze models. The end result is a quick, broad, exploratory analysis capability.

The SEED Center for Data Farming has completed over 50 studies while building this environment. Many of these studies are student theses—most of which are applications of the ideas to investigate a breadth of military and homeland security issues. The next three sections summarize three such examples. The SEED Center's web pages at <harvest.nps.edu> contain links to graduate

theses and other publications, spreadsheets and software for constructing experimental designs, and additional resources.

3 MARITIME PROTECTION OF CRITICAL INFRASTRUCTURE ASSETS

The Campeche Sound is an area of great economic importance to Mexico, and is the source of more than 83 percent of the petroleum produced in Mexico. Its strategic value and economic worth make these facilities one of Mexico's greatest assets. Much of that oil is sold to the United States, which makes these facilities a potential target for terrorist groups that want to harm either Mexico or the United States. Indeed, Al Qaeda called for attacks on countries that supply oil to the United States—and identified Mexico by name as a recommended target (NBC News 2007).

To protect this critical asset, Petroleos Mexicano (PEMEX) and the Mexican Navy maintain mutually supportive security strategies in the Campeche Sound. During a state of green alert (the normal posture), the force deployment in the operational area consists of the following:

- One HURACAN-class missile ship, SAAR 4.5, with a shipborne helicopter.
- Four POLARIS-class interceptor patrol boats.
- An E-2C HAWKEYE Airborne Early Warning (AEW) aircraft.
- A C-212 AVIOCAR Maritime Patrol Aircraft (MPA).
- An intercepting aircraft, type REDIGO.
- One helicopter, type MI-17.

These craft patrol and enforce prevention and exclusion areas that have been established. We focus our analysis on the surface zones. In the marine prevention area, there is a system of access control for all boats. In the exclusion area, the authorized navigation of boats to the facilities is allowed only after being verified by units of the Navy. Figure 1 shows the Campeche Sound, the numerous marine oil facilities, and the exclusion zones.

Are the existing assets and the accompanying tactics enough to protect these facilities from a terrorist attack? If not, what new capabilities or tactics are required? Should the protection zones be changed? Do incursions by the numerous fishing boats in the area create a vulnerability? These are but a few of the many questions that those in charge of protecting the Campeche Sound seek to answer. Ideally, one would want to experiment in the real world with different sets of equipment and their tactics against a variety of threats. Unfortunately, doing so may be impossible (the equipment may not yet be purchased), extremely expensive, or impractical (as this is a busy place). However, insights can be obtained quickly and inexpensively through simulation experiments. What follows is a summary of such experiments (Martinez 2005).

To examine the protection of Mexico's Campeche Sound marine oil facilities, a simulation was constructed using MANA as a distillation tool. In a distillation, the scenario abstraction strives to capture only the essence of the situation by avoiding unessential details. The threat chosen to test the Navy's defenses is a simultaneous attack by up to three high-speed boats acting as Kamikazes. This is similar to previous maritime terrorist attacks—such as the suicide boat attack on USS Cole. The terrorist boats are assumed to be loaded with explosives and each targets a separate critical platform. The threat is deemed successful if at least one critical platform is destroyed. The Mexican Navy's assets are a subset of the assets listed above. A success in stopping the terrorist boats' attack occurs when at least one Navy resource intercepts and kills the attacking boats with no damage to the hydrocarbon facilities. In addition, the situation is complicated by the presence of numerous fishing vessels and other ships working in the area. All of these ships must be identified and tracked. Figure 2 displays a screen shot of the implemented scenario in MANA.

All told, this simulation consists of hundreds of agents. Each has a set of capabilities, such as a maximum speed, sensing and communication abilities, and weapons. Furthermore, each agent has a set of desires. For example, the terrorist boats want to get to their targets, while avoiding the Mexican Navy's defenses. The Navy's assets want to identify and track all vehicles in the area. If a ship is in a zone that it is not allowed to be in, the Navy will attempt to get it to leave the area. If the vehicle does not respond, and it is within the exclusion zone, the Navy will attempt to destroy it sufficiently far from all platforms. The fishing boats and service vessels just want to go about their business—but may stray into areas they are suppose to avoid.

Many simulation experiments were run consisting of various combinations of Mexican Navy assets (controllable factors) and terrorist boat attacks (uncontrollable factors). We now describe one such set of experiments.

The controllable factors are the different combinations possible in the area that can be obtained by interchanging the key elements and practices of the overall naval force, including:

- Presence of the HAWKEYE AEW aircraft.
- Presence of the AVIOCAR MPA.
- Aerial patrol by aircraft, type REDIGO, or helicopter, MI-17.
- Patrol area of a HURACAN ship.
- Number of POLARIS interceptor boats in the area (0 to 2).

A full factorial design, with some constraints, results in 60 combinations of the Navy's assets. These factors were

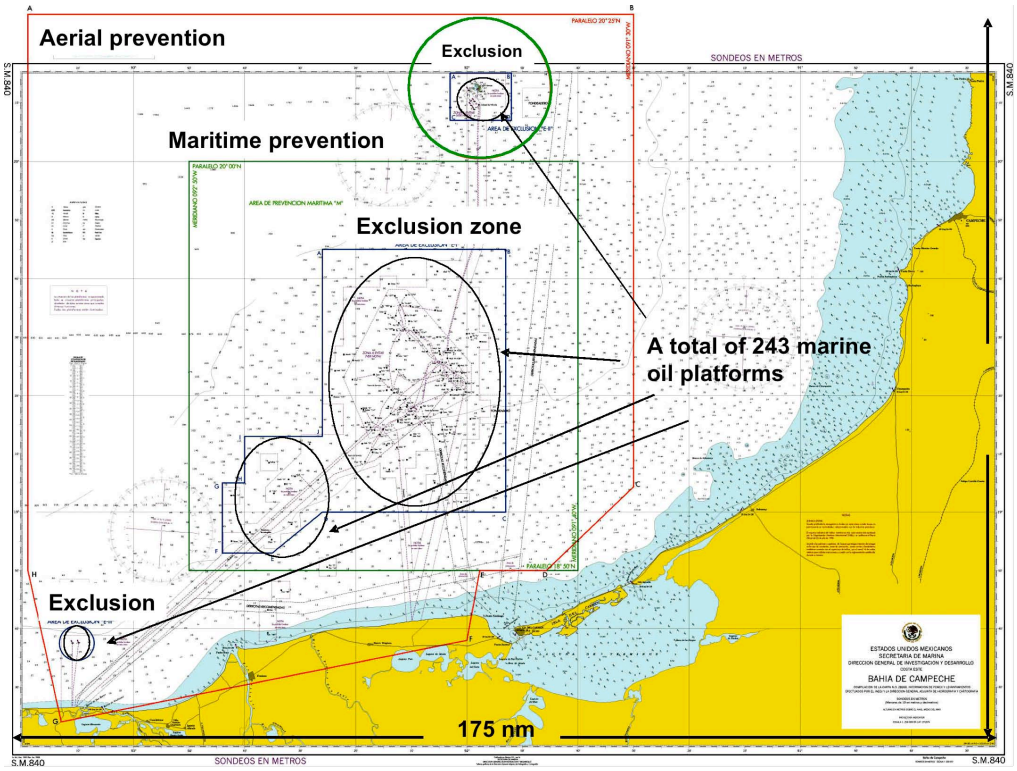

Figure 1: The Campeche Sound.

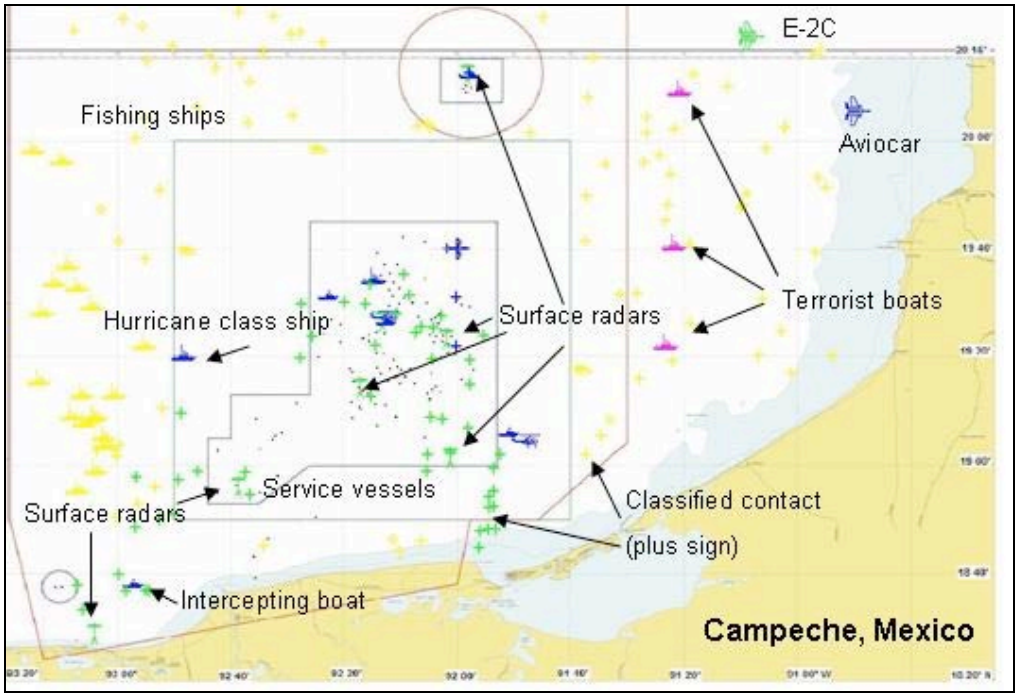

Figure 2: Screen shot of the MANA implementation of the Campeche Sound simulation.

chosen for exploration after many interactive runs (examining all of the Navy's assets) and numerous preliminary trials—many of the latter taken while developing and testing the model.

The uncontrollable factors varied in these experiments are the number of terrorist boats (from 1 to 3), the speed of those boats (from 20 to 45 knots), and the number of fishing vessels entering the forbidden area during the attack (from 0 to 5). A total of 17 combinations of these factors were obtained by using an orthogonal Latin hypercube from Cioppa and Lucas (2007), with rounding for the discrete factors.

The design for the controllable factors was crossed with the design for the uncontrollable factors. This ensures that each combination of controllable factors is run in similar uncontrollable (or noise) circumstances. The result is a total of $60 \times 17 = 1,020$ input combinations. Since MANA is a stochastic simulation, 50 replications were taken at each of these design points. This results in 51,000 simulated attacks. These experiments were conducted over a weekend using the Maui High-Performance Computing Center (MHPCC).

The analysis of the resultant output data used three primary analysis techniques: Regression trees (also called classification trees), regression analysis, and the one-way analysis of means of each of the critical factors in the model. Two types of analyses were done: one used all of the factors as independent variables, while the other allowed only the controllable factors into the models in order to seek robust maritime protection strategies. Figure 3 shows a regression tree constructed using all of the input variables. Here, the response is the proportion of successful attacks by terrorists—less being better.

The important insights found analyzing the full model are summarized in the following list:

- The most important factor in the probability of destroying at least one platform is the speed of the terrorist boats. Their speed limits the reaction time of the Mexican Navy. When the speed of the terrorist boats is slower, the terrorists can increase their chances of success by employing more boats.
- When the HAWKEYE AEW aircraft is present in the area, its early warning and broad surveillance capabilities provide a significant increase in the probability of destroying all of the terrorist boats.
- The probability of killing enemy terrorist boats before they reach an oil platform decreases when more than two fishing boats are in the maritime prevention area during a terrorist boat attack. Note: this result is gleaned from an expanded tree.

Insights on models constructed with only the controllable factors as independent variables include:

- Because of its long range surveillance radar for detection and classification, and significant communication capability, the HAWKEYE AEW aircraft is the most important of the controllable factors.
- When the HAWKEYE AEW aircraft is absent in the scenario, it is important that the AVIOCAR MPA (which serves in a very similar role as the HAWKEYE AEW aircraft, but with less range in its surveillance radar) be present in the area.
- The patrol area of the HURACAN ship is not important in the model. Both main patrol areas, the exclusion area and the maritime prevention area, have the same effect within the model.
- The HURACAN ship is only significant in the scenarios when it carries a shipborne helicopter.
- The additional POLARIS interceptor boats in the area are only significant if the route of the terrorist boats lies within their patrol area.
- The patrol areas of the REDIGO aircraft and the MI-17 helicopter patrolling are insignificant in the model. This does not mean that they are not necessary in the scenarios; it means that any of these units' presence in the area has the same effect.

The analyses that led to these conclusions can be found in Martinez (2005).

Once built, a simulation like this can be used to address many other question, such as alternative threats and potential future capabilities for the Navy to consider investing in. These can also include sensitive issues, such as the size and shape of the prevention and exclusion areas and the Navy's rules of engagement (ROE). It also suggests intelligence requirements. For example, the above analysis suggests that we should pay special attention to boats in the area that travel at or above 37 knots.

4 NON-LETHAL CAPABILITIES IN A MARITIME ENVIRONMENT

The terrorist attack on USS Cole on October 10, 2000 reenergized national efforts towards preserving freedom of the seas and safe access to ports, with a directed focus on force protection initiatives and technology. The tremendous potential of non-lethal capabilities in maritime force protection has been recognized by the Quadrennial Defense Review, as well as an independent study conducted by the Naval Studies Board. This research, sponsored by the Joint Non-Lethal Weapons Directorate, directly impacts the current development of non-lethal requirements and tactics needed for effective maritime security.

The following questions were identified by Sickinger (2006) for an entering port force protection mission:

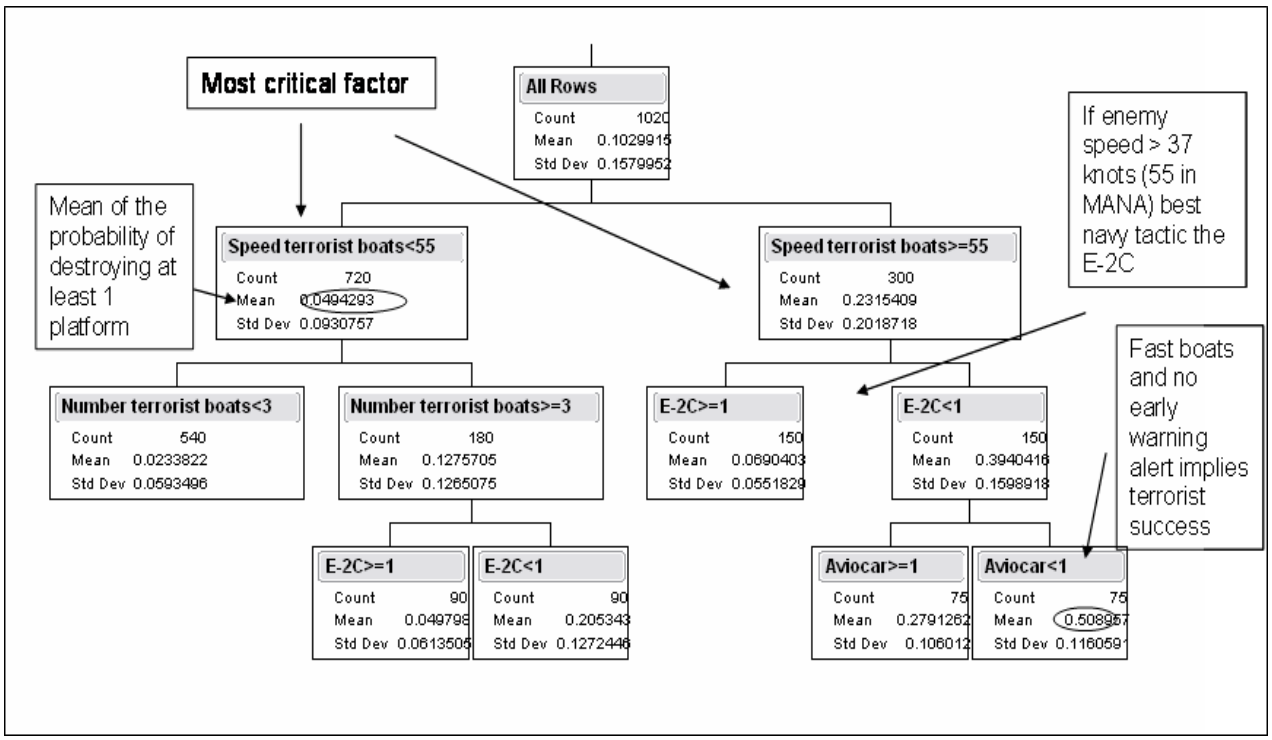

Figure 3: Regression tree on all factors for the Campeche Sound simulation.

- What non-lethal capabilities are required for a maritime force protection mission?
- When are non-lethal capabilities tactically appropriate?
- What are the geographical effects?
- How are non-lethal capabilities used to identify threats from nonthreats?
- Is MAS an appropriate modeling tool?

The first step in answering these questions was to develop a scenario within a MAS environment that appropriately emulated a Navy ship's ability to do three tasks: (1) identify potential threats; (2) determine intent of approaching small vessels; and (3) deter vessels from closing within the 100-yard naval protective zone.

Three reasons influenced the choice of PYTHAGORAS, a Northrop Grumman product, as the MAS. First, it offers a unique set of capabilities appropriate for this investigation. Specifically, PYTHAGORAS:

- Incorporates soft rules to distinguish unique agents;
- Uses desires to motivate agents into moving and shooting;
- Includes the concept of affiliation (established by sidedness, or color value) to differentiate agents into members of a unit, friendly agents, neutrals, or enemies;
- Allows for behavior-changing events and actions (called triggers) that may be invoked in response to simulation activities; and
- Retains traditional weapons, sensors, and terrain.

Second, PYTHAGORAS is specifically designed to be compatible with data farming, greatly facilitating the data collection effort. Third, as a U.S. developed model, this research can be applied to quickly assist our operating forces in exploiting vulnerabilities and determining tactics to mitigate risk within ports and choke points throughout the world.

The scenario chosen for virtual experimentation focuses on a U.S. Navy ship, returning to port, entering the Elizabeth River from Thimble Shoals Channel (Figure 4). This is a challenging scenario because of the constrained geography that the ship must transit. The situation is further complicated by numerous pleasure craft, fishing vessels, and merchant ships in the area.

The primary blue agent is the ship returning to port. The ship is equipped with three types of non-lethal weapons: an acoustic hailing device, an optical dazzler, and warning munitions. Of course, the ship also contains lethal means of keeping ships from getting too close. The goal is to use the non-lethal weapons to minimize the ship's vulnerability, while simultaneously minimizing the chances of engaging a neutral vessel with lethal weapons. The attacking (or red) agents vary in number and in tactics. Basically, they loiter among the civilian shipping, looking for opportunities to get close enough to the blue ship to cause it damage.

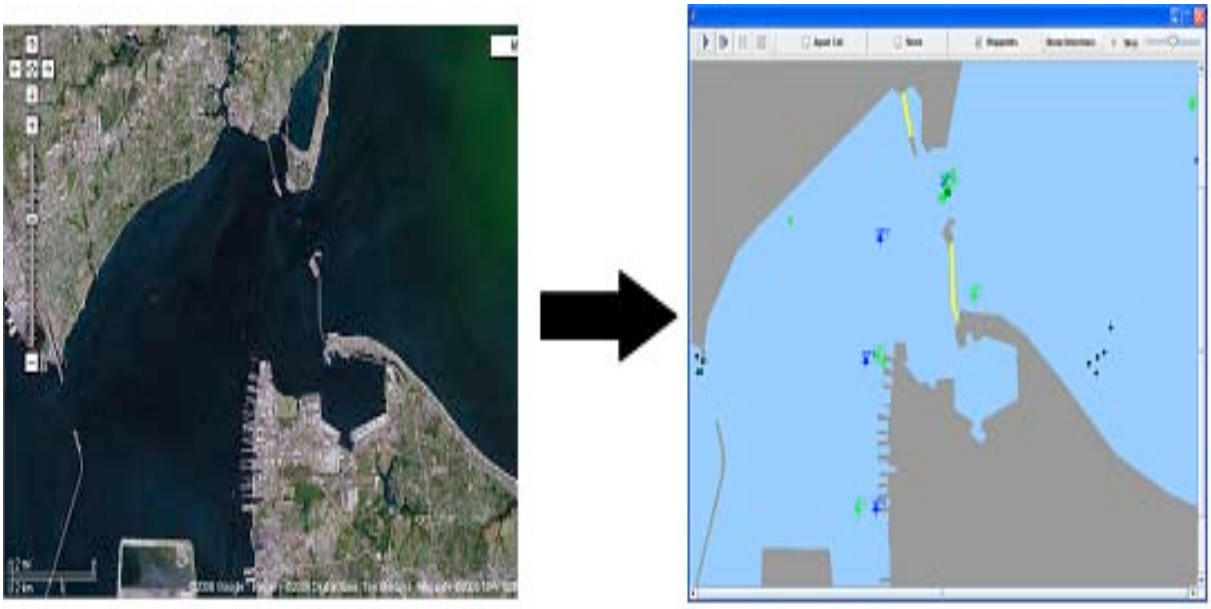

Figure 4: Actual terrain and the model's terrain for the Thimble Shoals Channel.

Once the scenario was developed, the next step was to apply an efficient design of experiment (DOE) and cluster processing in order to capture a wide region of possible outcomes. The final scenario was simulated over a range of 33 input variables. These input factors included everything from the number of hostile boats, to the requirements of the non-lethal capabilities, such as range and firing rates, to quantified intangibles, such as fear and aggression levels of inbound targets. Most of these factors are continuous, but a handful (like the number of threats) are integer.

Through the power of simulation, over three quarters of a million data points were generated over multiple iterations. The primary design technique used was, again, nearly orthogonal Latin hypercubes—with rounding for the discrete factors. Several iterations were made, typically involving tens of thousands of simulated port entries over a few hundred input combinations involving approximately 20 variables.

The key element in tying the data to the research questions were the measures of effectiveness selected for analysis. These were:

- *Deterrence ratio*: The percentage of time the targets are deterred.
- *Hostile identification ratio*: The percentage of time targets are identified as hostile, engaged, and subsequently killed, with lethal force.
- *Warning zone identification ratio*: Among those targets identified as hostile, the percentage of time identification occurs outside the threat zone using non-lethal capabilities.

Using multiple data mining techniques, ordinary statistics, and visualization tools, the mammoth amount of data was efficiently analyzed to provide insight on the research questions. Key insights into non-lethal requirements and tactical application (from Sickinger 2006) include:

- The employment of non-lethal capabilities is extremely effective when used to identify threats from nonthreats in an ambiguous situation.
- Inbound speed is the critical factor in identifying and engaging inbound hostile threats outside of the exclusion zone.
- The number of inbound targets has little to no impact on identification and engagement rates of hostile targets.
- The first response non-lethal capability is the most crucial in deterring nonsuicidal targets.
- The acoustic hailing device is significantly more effective when employment time is less than 30 seconds against hostile targets and one minute for neutral or loitering targets.
- When used alone, counterpersonnel non-lethal capabilities fail to deter loitering targets who attack when within close proximity.

With a limited number of non-lethal capabilities applied to a very specific mission, this thesis researched what other possible applications are appropriate using the methodology applied. Follow-on work was identified for three primary research areas:

Requirements: This research modeled three counterpersonnel, non-lethal capabilities. Future work is needed to expand scenarios to include countermaterial capabilities.

Tactics: The scenario simulated involved one primary tactic adapted from current U.S. Navy tactics. Future work should include a comparative analysis of new tactics, especially in areas where this research deemed current tactics fall short.

Vulnerability Assessments: In addition to exploring the requirements and tactics of the non-lethal capabilities, this research was very effective in exploring the geographic vulnerabilities of the modeled port. Given this success, applying this methodology to other geographic ports or choke points of interest could assist in anti-terrorism and force protection planning prior to ship arrival.

In summary, this research used cutting edge modeling and simulation to effectively emulate a complex scenario where little historical performance data exists. It produced valuable insights by applying proven operations research tools and techniques, and provides a revolutionary compliment to subject matter expertise in non-lethal requirements and tactics development early in the acquisition process.

5 EMERGENCY FIRST RESPONSE TO A CRISIS EVENT

Large-scale disasters can quickly overwhelm the capabilities of state and local governments. An effective response in these situations results from integrating state and local agencies with their federal counterparts, thus enabling the flow of needed resources and knowledge. Toward this end, a Presidential Directive was issued as part of a plan to prepare for and mitigate the effects of crisis events. This directive led to the establishment of the National Exercise Program (NEP). National-level exercises, such as those that comprise the NEP, test and evaluate federal, state, and local integration and readiness to confront a man-made or natural disaster.

Top Officials (TOPOFF) exercises are the foundation of the NEP. These large-scale exercises involve participation from all levels of governmental and nongovernmental agencies inside and outside the United States. These exercises are currently being planned and executed with very little consideration given to the value of simulation as a preparation tool.

Simulation is a widely used decision support tool because it allows staffs and decision makers to explore given problems in ways that are otherwise impractical (e.g., due to resources needed) or impossible (e.g., running an exercise with thousands of parameter permutations). The Department of Homeland Security (DHS) recognizes the value of simulation and reviews simulation models for applicability before each TOPOFF planning process begins. As yet, DHS has not found the right tool for the job.

Figure 5 demonstrates an organizational learning process adapted from a methodology developed by the U.S. Army Training and Doctrine Command Analysis Center Monterey (TRAC-MTRY). This methodology is an iterative process that uses a quick-turnaround, low-resolution model to provide initial insights into a given problem. Those insights are used in the execution of a high-resolution simulation, such as a wargame. As with any high-resolution simulation, wargaming results can be actionable results; that is, the decision maker can use these results to finalize the plan that was wargamed. However, the decision maker can also decide to adjust the low-resolution simulation and iterate the process until they obtain satisfactory results.

The process established in this research expands the TRAC-MTRY methodology, which includes a general flow that uses the power of simulation to train a given audience. This research shows a specific process by which low-resolution and high-resolution simulation can be used together to help organizations prepare for a TOPOFF exercise, or any other large-scale training exercise.

High-resolution simulations, such as wargames, are established decision support tools. TRAC-White Sands Missile Range developed a model to facilitate the execution of wargames in a first-response setting. The Emergency Preparedness incident Command System (EPiCS) was used in February 2006 to simulate emergency first response to a bomb attack in Baltimore's Inner Harbor area, during a festival. To assess and demonstrate the potential of an agile, low-resolution simulation in this methodology, a MAS was developed in PYTHAGORAS to simulate the same vignette. The simulation involves a small terrorist cell that detonates a car bomb, then works to further incite panic, while a gunman lies in wait for first responders to attack. Police, fire, and medical personnel respond to the bomb blast area, in which walking wounded and stretcher wounded civilians are panicking. First responders have the following priorities of work, in which police, emergency medical technicians, and firefighters will:

- Stabilize wounded civilians.
- Restore calm in the area.
- Eliminate further threats.
- Maintain the safety of the first responders.

An illustrated screen shot of the emergency first response MAS appears in Figure 6. Analyzing the first responder effectiveness involves exploring a 48-dimensional space to gain an understanding of the complex relationships involved in this problem. Furthermore, about half of these factors take on integer values. For example, the number of responders of various types in various locations (a dozen factors) is varied from 0 to 8. This exploration required an efficient design of experiments (DOE). A traditional factorial (gridded) design would have resulted in experimental runs that lasted 116 trillion times the current age of the universe.

The DOEs developed for this research uses both the flexibility of Flexible Random Latin Hypercube (FRLH)

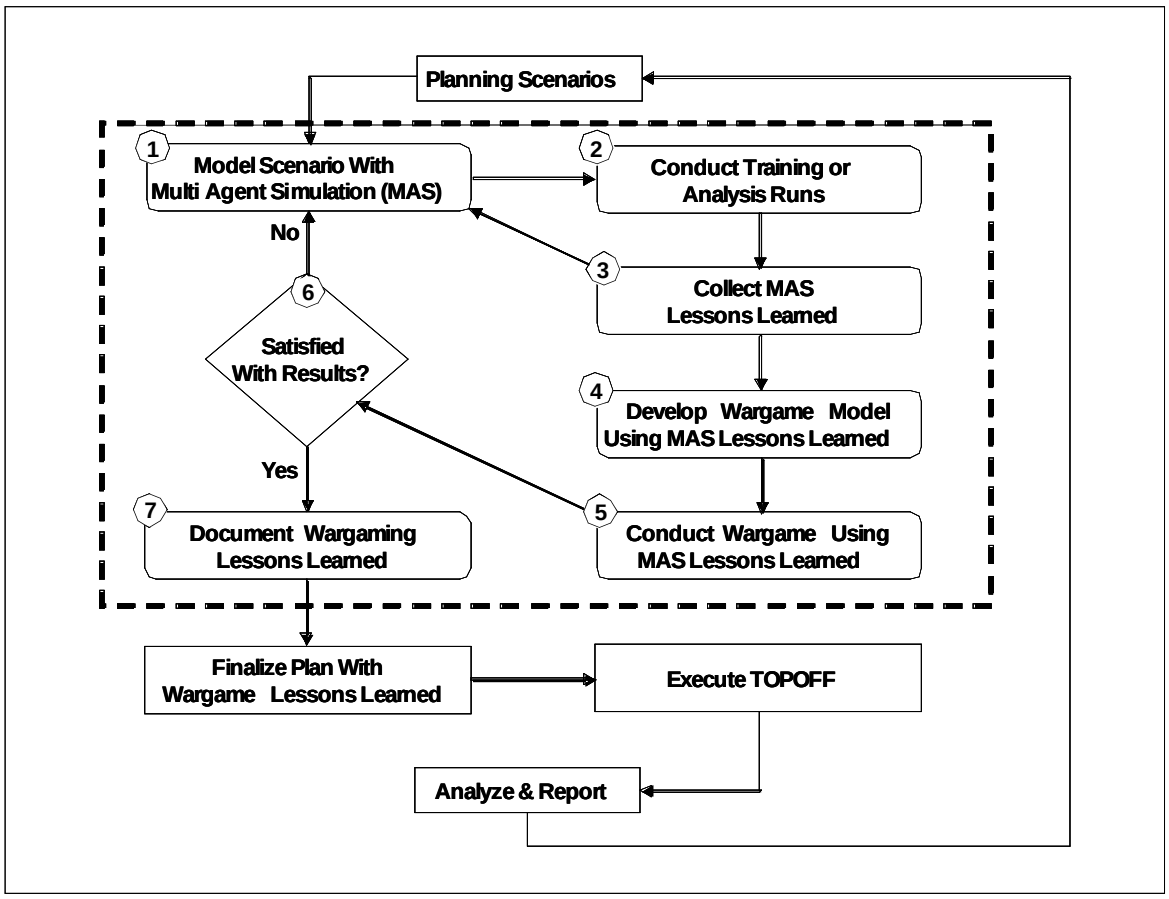

Figure 5: Adaptation of TRAC-MTRY's learning methodology.

sampling (Hernandez 2007), and the space-filling nature of Nearly Orthogonal Latin Hypercube (NOLH) sampling. Using 1,008 input combinations, Hernandez was able to generate a design matrix with a maximum absolute pairwise correlation of 0.001. Fifty replications were run per input combination. Despite the use of these highly efficient designs, 156 CPU centuries were required to complete the experiment. This was possible only by using the supercomputers at the Maui High Performance Computing Center (MHPCC). The data set analyzed contained over 50,000 rows by more than 5,000 columns.

The analysis of the data from this model (see Roginski 2006 for details) suggest the following:

- Overwhelmingly, the most important factor in achieving success in crisis mitigation is the effectiveness of the police in taking positive control of the crowd, exerting calming influence, and providing direction.
- If a police force is not well trained, and therefore not very effective, the officers may achieve greater success by being less persistent with individuals; that is, by spreading their influence more broadly.
- Well established, well executed standing operating procedures (SOPs) may play a more important role in first response operations than interagency communication.
- There may be a level of diminishing returns for first responder training; that is, a person can be only so trained. After that level is reached, it may be more effective to leverage resources elsewhere.

The results of the data analysis are not meant to directly apply to actual emergency response techniques, or specifically to the City of Baltimore. This model does not include the actual force structure and SOPs from Baltimore, but data adapted from the February 2006 EPiCS run. This research is a proof of concept to show that it is possible to quickly and credibly model emergency first response with a MAS, and the data analysis from such a credible, verified, and calibrated model will be useful and insightful.

The single most important result of this research comes not from the data analysis, but from the developed methodologies. Simulation is a decision support technique that is relevant to emergency preparedness, especially to an exercise program the size and complexity of the TOPOFF program. The organizational learning technique discussed

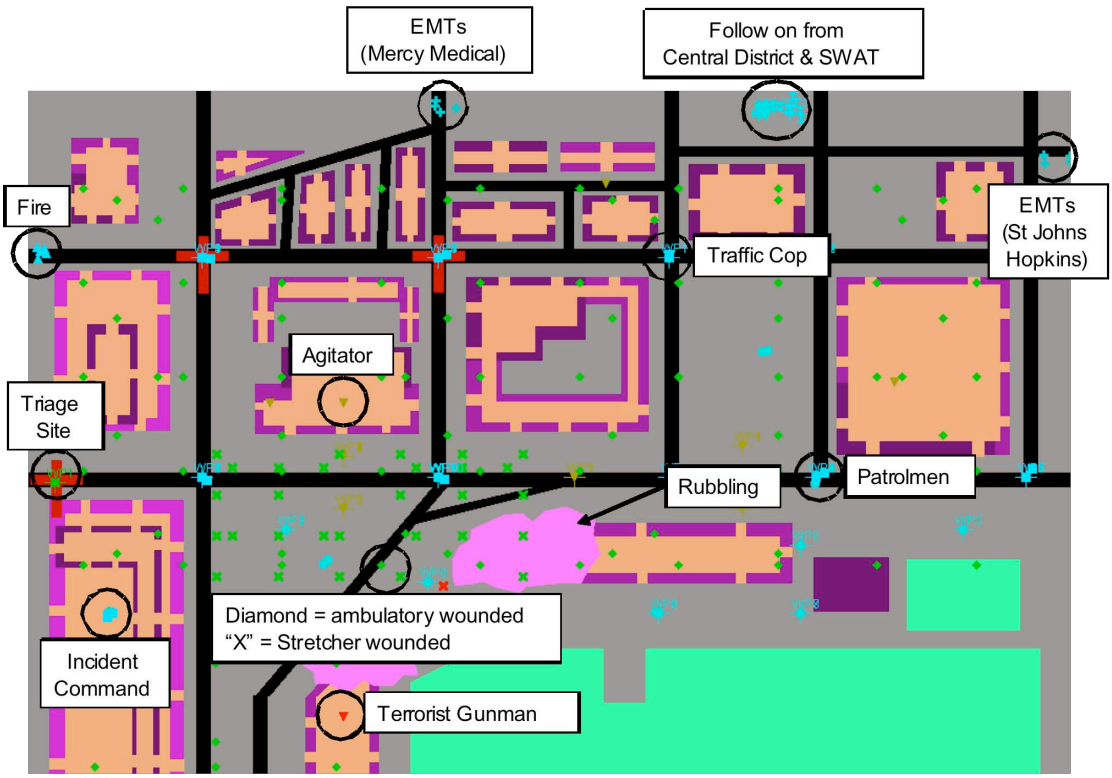

Figure 6: Screen shot of emergency first response multi-agent simulation.

herein and the incorporation of MAS in emergency first response simulation can help train first response organizations more effectively, resulting in better crisis mitigation and lives saved.

6 SUMMARY

This paper summarizes three diverse applications of MAS to national security issues. We could have shown dozens more. Our emphasis is on the types of analyses one can perform, and the types of insights obtainable, by using efficient, high-dimensional designs to explore MAS. Due to space limitations, we have barely touched on the analysis behind these insights. Interested readers are encouraged to read the theses of Martinez (2005), Sickinger (2006), and Roginski (2006) for more details on the simulations, experimental designs, and analyses.

Simulation experiments are a valuable tool in studying defense and homeland security issues. One need not look too hard to see similarities between many national security features and key aspects of MAS. Simple MAS have already proven useful in generating insights and focusing high-resolution simulation experiments. For both of these purposes, the utility of MAS is enhanced by an infrastructure that allows analysts to quickly build, run, and analyze many thousands of simulation experiments over a broad range of input variables. The SEED Center for Data Farming is researching ways to do this more efficiently and enable more analysts use these tools and ideas.

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REFERENCES

Bitinas, E. J., Z. Henscheid, and D. Middleton. 2006. *Pythagoras (Version 1.10) User's Manual*. Northrop Grumman Corporation, Washington, D.C.

Cioppa, T. M., T. W. Lucas, and S. M. Sanchez. 2004. Military applications of agent-based simulations. In *Proceedings of the 2004 Winter Simulation Conference*, ed. R. G. Ingalls, M. D. Rossetti, J. S. Smith, and B. A. Peters, 171–180. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Cioppa, T. M., and T. W. Lucas. 2007. Efficient nearly orthogonal and space-filling Latin hypercubes. *Technometrics* 49(1): 45–55.

Galligan, D. P., M. A. Anderson, and M. K. Lauren. 2004. *MANA: Map Aware Non-uniform Automata Version 3.0.37 User's Manual*. Auckland, New Zealand: New Zealand Defense Technology Agency.

Hernandez, A. 2007. Flexible random Latin hypercubes, Working paper, Department of Operations Research, Naval Postgraduate School, Monterey, California.

Hodges, J. S., and J. A. Dewar. 1992. Is it you or your model talking? A framework for model validation. Report R-4114-AF/A/OSD, RAND Corporation, Santa Monica, California.

Illachinski, A. 1997. Irreducible semi-autonomous adaptive combat (ISAAC): An artificial life approach to land warfare. Research Memorandum CRM 97-61, Center for Naval Analysis, Alexandria, Virginia.

Kleijnen, J. P. C., S. M. Sanchez, T. W. Lucas, and T. M. Cioppa. 2005. A user's guide to the brave new world of simulation experiments. *INFORMS Journal on Computing* 17(3): 263-289.

Lucas, T. W. , S. M. Sanchez, L. P. Brown, and W. Vinyard. 2002. Better designs for high-dimensional explorations of distillations. In *Maneuver Warfare Science 2002*, ed. G. E. Horne, 17–46. Quantico, Virginia: Marine Corps Combat Development Command.

Martinez, F. 2005. *Maritime protection of critical infrastructure assets in the Campeche Sound*. M.S. thesis, Department of Operations Research, Naval Postgraduate School, Monterey, California.

NBC News. 2007. Venezuela bolsters oil security after threat. Available via <www.msnbc.msn.com/id/17149034/> [accessed July 15, 2007].

Roginski, J. W. 2006. *Emergency first response to a crisis event: A multi-agent simulation approach*. M.S. thesis, Department of Operations Research, Naval Postgraduate School, Monterey, California.

Sacks, J., W. Welch, T. Mitchell, and H. Wynn. 1989. Design and analysis of computer experiments. *Statistical Science* 4(4): 409–435.

Sanchez, S. M., H. Wan, and T. W. Lucas. 2005. A two-phase screening procedure for simulation experiments. In *Proceedings of the 2005 Winter Simulation Conference*, ed. E. Kuhl, N. M. Steiger, F. B. Armstrong, and J. A. Joines, 223-230. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Sanchez, S. M., H. Wan, and T. W. Lucas. 2007. A two-phase screening procedure for simulation experiments. Working paper, Department of Operations Research, Naval Postgraduate School, Monterey, California.

Sanchez, S. M. and T. W. Lucas. 2002. Exploring the world of agent-based simulations: Simple models, complex analyses. In *Proceedings of the 2002 Winter Simulation Conference*, eds. E. Ycesan, C.-H. Chen, J. L. Snowdon, and J. M. Charnes, 116-126. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Sanchez, S. M. and P. J. Sanchez. 2005. Very large fractional factorials and central composite designs, *ACM Transactions on Modeling and Computer Simulation* 15(4): 362–377.

Sickinger, L. R. 2006. *Effectiveness of non-lethal capabilities in a maritime environment*. M.S. thesis, Department of Operations Research, Naval Postgraduate School, Monterey, California.

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