An Agent-Based Modeling Approach to Quantifying the Value of Battlefield Information

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Introduction

Despite increased investments in military tactical information systems, the analysis community has great difficulty in quantifying the contribution of these systems to the overall fight, in answering the question, "How much is a pound of C4ISR worth?" The Army's Objective Force Maneuver Unit of Action (UA) intends to further increase its information advantage. "Able to ***see first and understand first*** with combat information on terrain and weather, Red and Blue forces and noncombatants tailored to unit task and purpose, the UA will develop the situation, out of contact, and establish a dynamic tactical information sphere in order to determine when and where to fight on favorable terms."[1] However, the Military Operations Research Society Workshop on Advancing C4ISR Assessment concludes that analysis of major combat operations would benefit from improved modeling tools for command and control, for behavior modeling, and for assessing the contribution of C4ISR (Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance) relative to weapons.[2]

This paper proposes agent-based modeling as a methodology that allows the military analyst to quantify the value of information as follows: "The value of combat information to A Company, if they act upon it, is a 380% increase in enemy losses with no significant change in friendly losses." To be more specific, the networked C4ISR systems available to A Company in the given scenario allowed them to destroy 3.8 times more targets with no significant change in friendly losses.

Agent-based modeling fills a critical gap in military modeling capabilities, the ability to model how a combat soldier makes a tactical decision. That decision leads to a tactical action that allows that soldier to leverage the value of information. This article first identifies the existing gap in modeling capabilities. It then introduces agent-based modeling as a technical approach to filling that gap. It then presents two tactical decision making agents, the position agent and the route agent, as examples. These agents use information available to combat units in order to allow them to seek a position of advantage as they maneuver through complex terrain and enemy fire toward an objective. In an experimental scenario, routes generated by these agents, when evaluated in a high-resolution combat model, led to a significantly better mission performance. That mission performance improvement is the quantifiable value of battlefield information.

A Gap in Modeling Capabilities

An assessment of existing modeling capabilities identifies a critical gap in the ability to quantify the effects of an information gain, as shown by the knowledge hierarchy in Figure 1. At the lower end of the pyramid, existing combat models represent the physical effects of target acquisition and the dissemination of its reports across the battlefield. At the top of the pyramid, combat models simulate the combat effects of tactical action as it relates to attrition and control of terrain on the tactical battlefield. The gap is in the middle. The largely human process that translates battlefield information collected by C4ISR systems into decisions which organize and direct battlefield systems to gain a position of tactical advantage in order to accomplish friendly missions is not well modeled. This decision making process brings

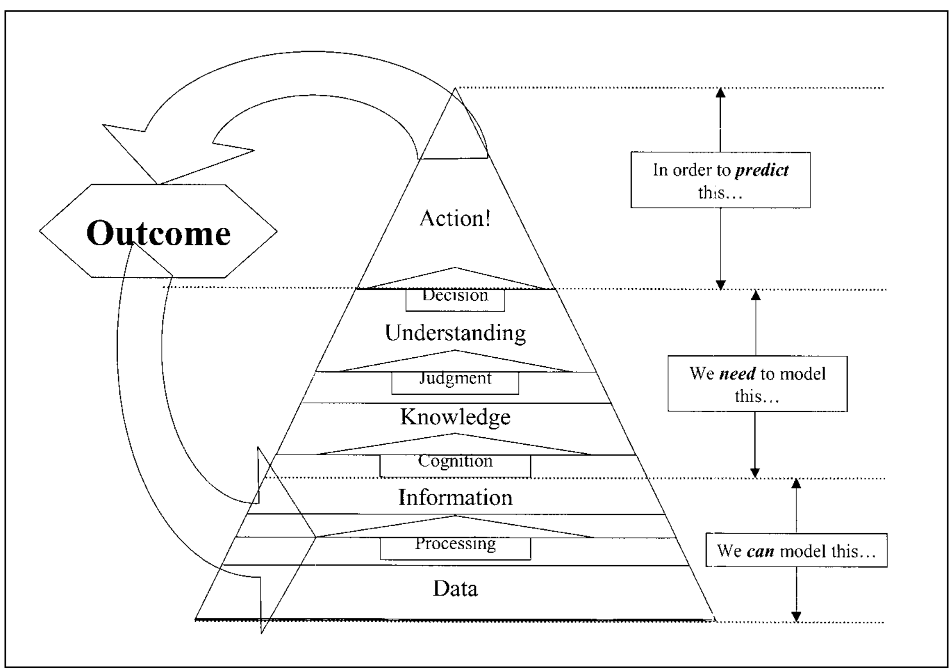

Figure 1. Combat models are able to model the effects of collecting data and information (bottom of the pyramid) and the effects of tactical actions (top of the pyramid). The gap is in the middle where models have trouble translating the information collected into knowledge and understanding which allow a tactical decision to take a different action.

value to the networked force. The information on the network has little intrinsic value. It is only valuable to the extent to which it allows decision makers to direct tactical forces on the battlefield to better accomplish the unit's mission. Embedding decision agents in combat models is one technical approach to filling this modeling gap in order to better quantify the value of network-centric capabilities.

Agent-Based Modeling

Agents are programmed software modules that scan their environment and make a decision.[3] In a military context, these decisions may be local decisions, such as moving one vehicle to avoid incoming fire, or global decisions such as the allocation of fire missions to a suite of shooters in order to engage the known set of targets. An agent-based model is one in which the connections and interactions among the agents has significant effects, as compared to the individual actions of any particular agent. These interactions give rise to emergent properties. In a complex system, emergent properties are those trends that, although not explicitly modeled, consistently arise out of the interactions between agents. Agent-based models are designed not as much to predict detailed outcomes as to gain insights and understanding of the system.[4] The increased capability of network-centric forces, if it really exists, is an emergent property. It cannot be proven with attrition-based equations of combat. However, in an agent-based model, a large number of unit agents use network connectivity to enhance their ability to interact with each other and the environment. If greater combat capability emerges consistently from these improved interactions, then analysts can gain some analytical insight about the potential combat capability of network-centric forces.

Supporting Research

This article represents a cross-fertilization and extension of two separate research projects at the United States Military Academy (USMA) Department of Systems Engineering. The Irreducible Semi-Autonomous Adaptive Combat (ISAAC) system is a well-documented agent-based model of greatly simplified land combat.[5] USMA Department of Systems Engineering researchers conducted a study using ISAAC to better quantify C4ISR effects on a simplified battlefield. Their research showed an improved performance of information-enabled forces, particularly if those forces were able to adapt their tactics to take better advantage of the improved information flow.[6] In another USMA experiment, adaptive decision-agents in the Combat Operations Support System for Adaptive Command and Control (COSSACC) developed an operations order, modified tactical routes, and adjusted positions of tactical forces to better attain higher-level objectives.[7] These agents, when used for decision support, improved the performance of the force in a detailed combat simulation. A natural next step was to combine the methods of these two projects using an accredited simulation system.

JCombat – An Agent-Based Combat Model in Java

In order to integrate agents from the COSSACC system into a more detailed simulation model, this project's analysts developed JCombat, a high-resolution, moderately-detailed, but fast-running combat simulation written in Java. JCombat exists as a test bed for command and control agents for potential integration into even more detailed accredited simulation models. It contains a detailed terrain model and line of sight algorithms. It handles direct fire in great detail. However, programming time constraints and an interest in execution speed forced a more abstract representation of target acquisition, communications and intelligence processes. In this initial experiment, there was no representation of indirect fires.

The JCombat simulation contains enough detail to allow the friendly force to receive a set of spot reports, build a partial common operational picture for the friendly force, and disseminate that picture to subordinate units for decision making. This common operational picture, along with some friendly objectives, was used by each unit in the friendly force to continuously update its routes and positions during the fight to seek a position of advantage and better accomplish unit missions. Two decision agents performed these tasks, the position agent and the route agent.

An operations order in JCombat may, instead of specifying an explicit route for a unit, give the unit a movement technique and allow the route agent to generate the unit's route. This movement technique defines the objectives a unit should seek as it develops its route. For example, the assault movement technique seeks speed and enemy destruction, while the recon technique seeks enemy acquisition as opposed to destruction, with little emphasis on speed. This is accomplished by a linear value model which assigns weights to the individual tactical characteristics of the route. The route evaluation model determines the average friendly rate of attrition against known enemy encountered along the route, the average enemy rate of attrition against the friendly unit as it traverses the route, the average number of enemy vehicles seen while traversing the route, and the total time required to reach the end of the route. For an assault, the value model assigns a weight of 100 to attriting the enemy, 80 to avoiding attrition, 30 to finding the enemy, and 40 to minimizing time. For a recon movement technique, the value model assigns a weight of 10 to attriting the enemy, 100 to avoiding attrition, 100 to finding the enemy, and 10 to minimizing time. These weights may be adjusted by the analyst to represent different value scores for different movement techniques.

A genetic algorithm evolves successive populations of routes for evaluation by the route evaluation model. The route planning genetic algorithm used by the route selection agent was adapted from the works of **Hocaoglu** and **Sanderson** and **Xiao** et. al.[8,9] The genetic algorithm represents a route as a variable length list of points through which a unit must pass while moving from its current destination to its final destination. Each point is an x,y coordinate pair in the continuous domain. In this representation, a unit's route may have from zero (move straight to destination) to any number of waypoints evolved by the algorithm. The algorithm adds a point to a route by inserting a knot point along one of the route legs. The point insertion algorithm first chooses one of the route legs at random. In Figure 2, the algorithm has randomly selected leg 2 from the three possible route legs. It then randomly chooses an interim point along that leg at which it will insert the knot point. It then must determine a knot distance. The knot distance is a random value drawn from a normal distribution with a mean of zero and a standard deviation of 1/2 the length

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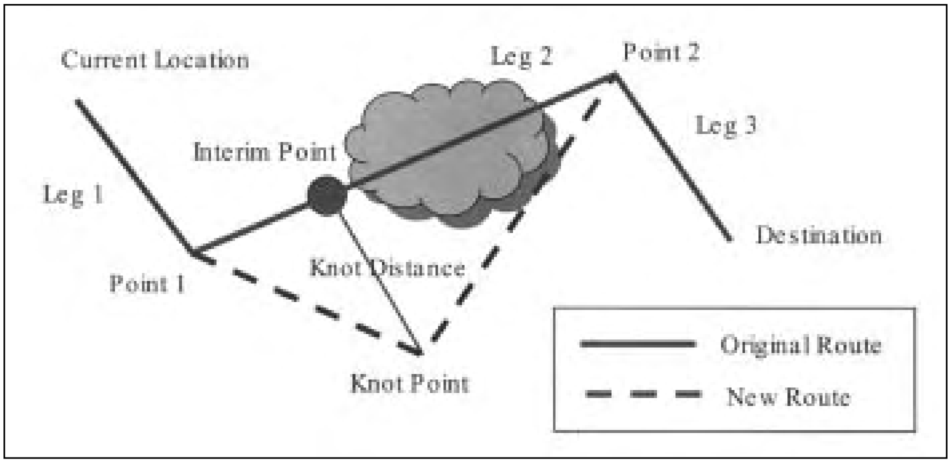

Figure 2. The process of adding a random point to a route. The knot point is inserted between points 1 and 2 to generate the new route shown by the dotted line.

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of leg 2. If the knot distance is positive, then a knot point is inserted perpendicular to one side of the leg. If the knot distance is negative, the knot point is inserted perpendicular to the other side of the leg. In Figure 2, the knot point has been inserted perpendicular to leg 2 and knot distance from the interim point. The knot point is inserted in the route between points 1 and 2 to give a new route shown by the dotted line.

Upon initialization, the route genome draws the initial number of points from a truncated exponential distribution with a mean of 1. It is most likely to have 0 points, next most likely to have 1 point, and so forth. For all initial points, the genome adds a random point to the route using the algorithm shown in Figure 2. Upon crossover, two routes will perform single point crossover in order to form two offspring for the next generation. Upon mutation, the route genome will successively test each of its points for mutation. If a mutation trial is successful, one of three things will happen to the point, each with equal probability. The genome may remove the mutated point, the genome may add a random point to the route, or the genome may remove the mutated point and add a random point to the route. As a unit moves, the route selection agent re-evaluates its current route at fixed time intervals. If the genetic algorithm finds a better route, it will replace the current route. This allows a unit to adjust to the changing enemy situation as it moves.

A unit may adjust not only its route, but also its final destination, bounded by the flexibility distance given by the planning agent. In a manner similar to the one used by the route selection agent to evaluate routes for a given movement technique, the positioning agent evaluates candidate positions for a mission given by the planning agent – attack by fire, support by fire, defend, recon, delay or hide. A mission is a set of objectives sought by the unit when it reaches its destination. For example, both the attack by fire and support by fire missions seek enemy destruction. However, the support by fire mission also places greater emphasis on staying close to the location given by the planning agent, so that it does not get too far away from the unit whose movement it supports. Since the search for a single position is a much simpler search task than the search for a route, the positioning agent uses a simple uniform random search as opposed to a genetic algorithm. At constant intervals, the agent uniformly selects a set of random points from within a circle (see Figure 3). The center and radius of the circle are determined by the location and flexibility distance given to the unit in its initial orders. A position evaluation model takes into account the surrounding terrain and enemy forces to give estimates for percentage of enemy units acquired, expected number of enemy vehicles destroyed, and expected number of friendly vehicles

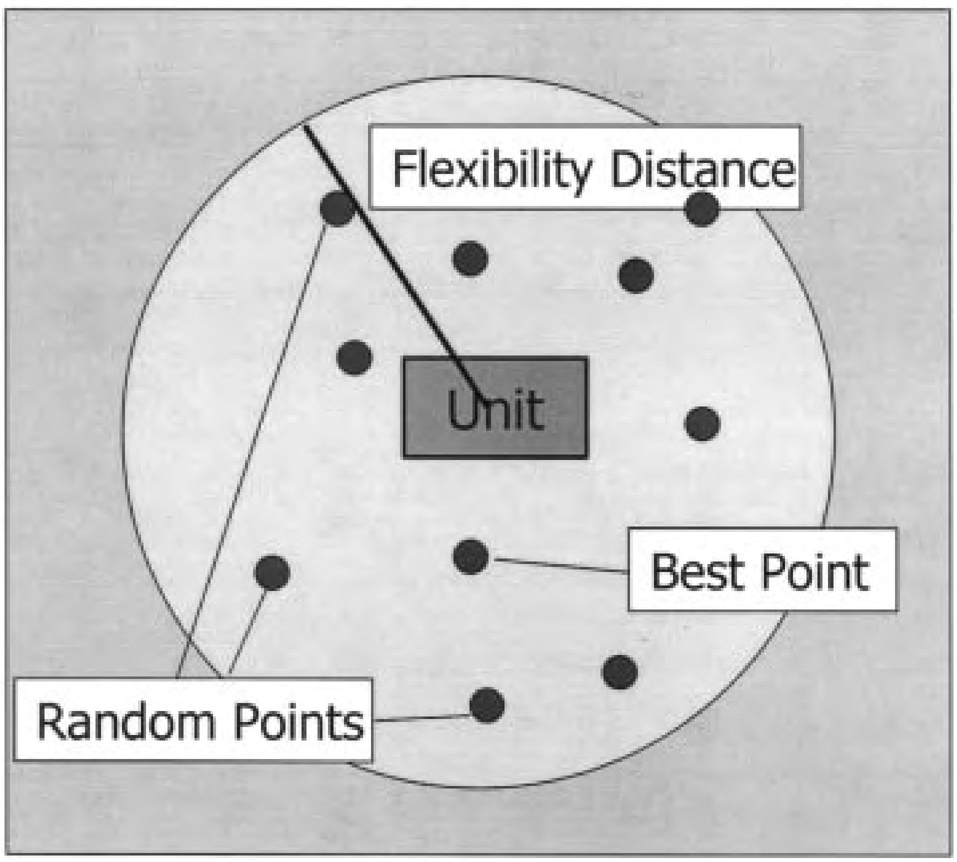

Figure 3. The process of selecting a new location. The evaluation model evaluates number of uniformly distributed random points within the flexibility distance. The position agent then moves the unit to the best point.

destroyed from each selected location. It also considers the distance from its assigned location. Based on its mission, the agent aggregates these criteria using a linear weighted value system to get an overall score for each location. This position value model is similar to the route value model used by the route agent. The agent will order the unit to reposition to the best location found.

By these techniques JCombat runs were able to generate potential improvements in the routes and positions occupied by forces during a battle. Using the route agent and the position agent, this model filled the middle gap in the knowledge hierarchy in order to translate the information in the common operational picture into tactical decision to change the routes and positions units used during the run in order to better accomplish their assigned missions.

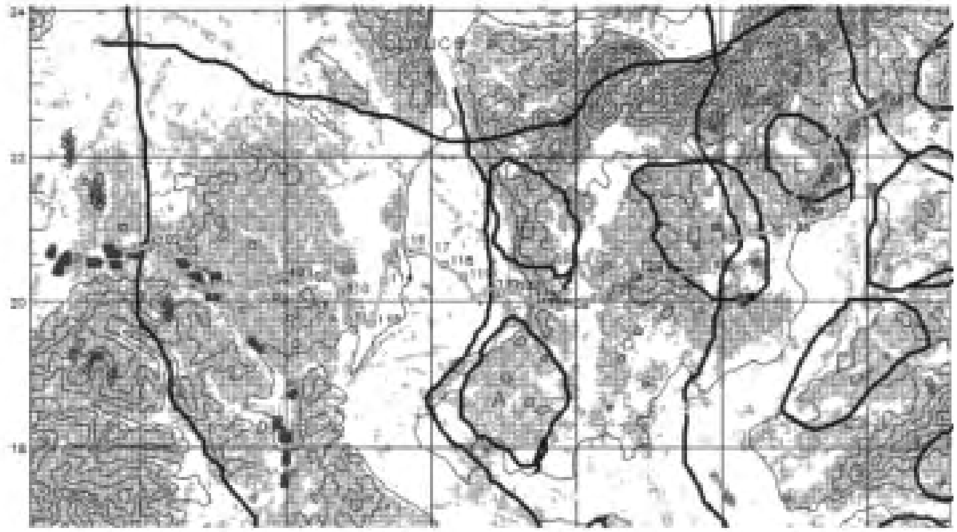

Figure 4. Experimental Scenario – CASTFOREM Screenshot. Elements of an allied tank-heavy company-team (left) must cross a valley and attack to destroy dispersed and well-hidden elements of a defending enemy force (right). In the base case, allied forces attacked in formation using the pre-scripted route shown here.

Value of Information Experiment

In order to quantify the value added to the force by the information-enabled tactical decision agents, analysts designed an experiment to evaluate the results of JCombat agent-based runs in a high resolution combat model. This experiment used a simple scenario in the Combined Arms Support Task Force Evaluation Model (CASTFOREM). In this scenario, an allied tank-heavy company-team had to attack across a valley to destroy elements of a defending enemy company. Prior to the attack, two unmanned aerial vehicles and a scout platoon conduct a reconnaissance to determine the disposition of enemy forces (see Figure 4). The first step was to synchronize the scenario between JCombat and CASTFOREM (see Figure 5). Analysts then evaluated the base case using a static course of action in the CASTFOREM scenario. For different treatments, routes generated by offline JCombat runs provided inputs to "agent-enabled" runs (see Figure 6). It is important to note that any qualitative judgment about the tactical soundness of the agent-based routes can only be gained from observation. These quantitative agents are not capable of explaining themselves in tactical terms. Analysts compared the results of the static runs to the agent-enabled runs in order to quantify the value of information-enabled decision making.

Table 1 shows the number of losses for each side during the CASTFOREM runs.

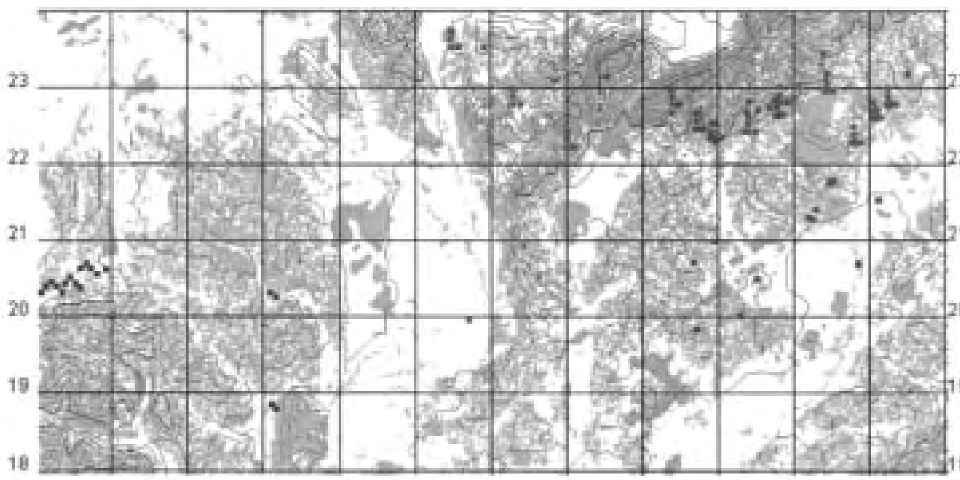

Figure 5. Experimental Scenario – JCombat Screenshot. This JCombat scenario has been synchronized with terrain, unit positions, and routes from the CASTFOREM scenario in Figure 4.

The runs are ranked by number of losses to support non-parametric statistical analysis of the difference between the two treatments. Note the preponderance of high attrition for red occurred during the agent-enabled runs. Using the Wilcoxon Rank-Sum test for differences in means, this difference in enemy losses was statistically significant at the 0.008 level.[10] There was no statistical difference in friendly losses between these treatments. Figure 7 is a graphical depiction of these results. The agent-enabled forces showed a 380% increase in enemy losses with a slight but statistically insignificant decrease in friendly losses. This sort of increase in mission effectiveness, with no increase in risk to friendly forces, represents the blue force's capability to transform information, via tactical decisions, into combat advantage.

Conclusions

Agent-based modeling has demonstrated an ability to quantify the value of tactical information. In a small scale tactical simulation, the position agent and the route agent serve as proxies for human decision makers. They translated situation awareness information about the enemy and the terrain into tactical decisions which provid-

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sored by the Naval Surface Warfare Center; "Reception, Staging, Onward Movement, and Integration (RSOI) in North East Asia," sponsored by the Center for Army Analysis; and "US Coast Guard Island Class Cutter Conversion Scheduling Optimization," sponsored by US Coast Guard Headquarters. It should be noted that several faculty members have security clearances, and some of the sponsored projects done were classified.

Going hand in hand with teaching is a significant and growing research agenda on Defense related issues. To facilitate this growth, the Systems Engineering and Operations Research Department has established a new Homeland Security and Military Transformation Laboratory that encompasses such efforts as designing a new fusion technique that can assist in detection of multi-site terrorist attacks; designing a system for tracking and identifying time-critical ground targets using multisensor tracking and fusion; developing a training program for intelligence analysts; and creating an information architecture for missile defense as part of Missile Defense Agency's Project Hercules. The efforts of the lab also focus on the enhancement of military capabilities through improved use of information. Research in this area includes optimization of Army's unattended ground sensor network, and the development of decision support techniques to assist Army planners in force structure determination. Work has also begun on a new research building on the GMU campus. Plans call for a new Military Operations Research Laboratory that will provide space and resources for faculty and student research.

The goal of the Military OR program at George Mason University is to produce knowledgeable OR analysts who can help solve the pressing problems of the US Military, to maintain close ties with the Military OR community, and to continue performing important research in military methodology. Detailed information about the programs is available at http://www.seor.gmu.edu. ✪

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ed a combat advantage. They are the key technology to fill a critical gap in modeling capability, the ability to translate battlefield information into actionable decisions which affect the outcome of the battle. In this particular case, the available situation awareness information and resulting actions yielded a significant increase in the ability to destroy enemy forces on the tactical objective without sacrificing survivability.

Agent-based modeling has great potential applicability in the analysis of C4ISR systems. Since these systems themselves don't attack targets or seize and hold terrain, their value added to the tactical unit is difficult to quantify when compared to other alternatives such as more forces or improved weapons. The first step would be to develop a suite of low-level tactical agents with capabilities similar to the route agent and the position agent. Different agents are necessary to perform different tactical decision making functions. Next, these agents should be integrated into an existing high-resolution combat model where they can make decisions based on the simulated situation awareness available to different units. This technical approach would provide an analysis tool capable of measuring, with comparable measures of mission performance, the value added of C4ISR systems and weapons systems. Such an analysis tool would have great potential to inform force design decision

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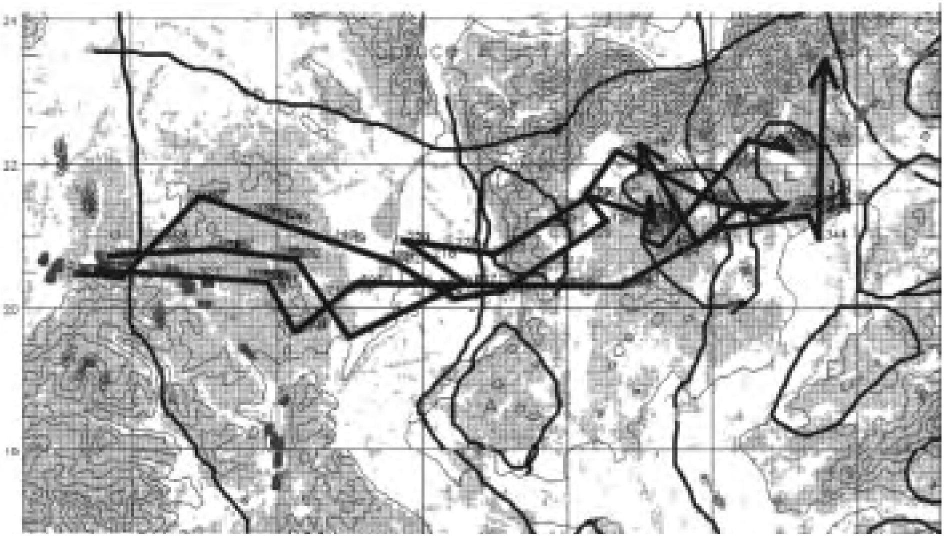

Figure 6. Agent-Based Routes. The position agent and route agent in JCombat generated the routes shown here for evaluation in CASTFOREM. Note that the agent-enabled routes, while generally seeking covered and concealed movement, took more risk by occasionally darting closer to the mountains to engage enemy forces from positions of advantage.

RED LOSSES

Losses	Run	Rank
0	Base	1.5
0	Base	1.5
1	Base	4
1	Base	4
1	Agents	4
3	Base	6
4	Agents	7.5
4	Agents	7.5
5	Agents	9.5
5	Agents	9.5

BLUE LOSSES

Losses	Run	Rank
3	Base	1
4	Agents	2
4	Agents	3
5	Base	4
5	Agents	4
5	Agents	6
6	Base	7
6	Base	8
6	Agents	9
7	Base	10

Table 1. These tables rank the number of losses for enemy (red) and friendly (blue) losses in the ten CASTFOREM runs. The agent-enabled runs showed a statistically significant increase in red losses with no statistically significant difference in blue losses.

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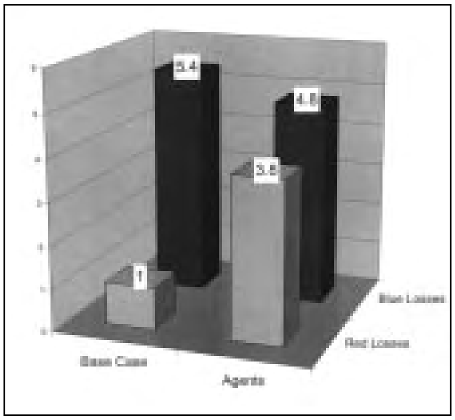

Figure 7. Mean performance of forces from 5 CASTFOREM runs for each of the two treatments. The agent-enabled forces destroyed 3.8 times more enemy forces with no significant difference in friendly losses.

makers as they seek to provide the proper mix of soldiers, weapons and information systems to current and future combat units.

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Biographies

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PLANNING
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efforts – many thanks! Of key importance to you is bus transportation on and around Quantico. Buses will be running throughout the day from the MORS parking area to the Symposium buildings and will run to the Club during lunch. Buses will also be provided, for your convenience in traveling, between MORS hotels and Quantico each morning and afternoon. If you drive, please park only in the MORS labeled parking lots. For more information on the Quantico area, please see Major Whaley's article in this issue of *PHALANX*.

I have mentioned a few of the key people, but by no means all, who are working hard to put on the Symposium for you. No list is complete without mentioning the dedicated professionalism of the MORS office. **Brian Engler**, **Natalie Strawn Kelly**, **Cynthia Kee**, **Corrina Ross-Witkowski** and **Jarvey Nelson** are the glue keeping everything together. During your time at the Symposium please take time out to thank them and all the dedicated group of volunteers that have worked for over 12 months to make this Symposium the best ever.

I hope to see all 10-12 June at the 71st MORSS! ✪

MORS PRESIDENT
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profession must push the development of improved means and processes that will support the attainment of credible, responsive and efficient analyses of Joint military operations, employing both current and proposed systems, tactics, and doctrine, in varying terrain, against both conventional and asymmetric adversaries, across the spectrum of conflict. No small order but we as a profession and as a Society need to "quicken the pace" in the attainment of this goal.

A second major challenge is to seriously consider the analytic consequences of the formation of the Department of Homeland Security. The simple titles by which the Department of Defense and the Department of Homeland Security are referred leaves little room for distinction. In my estimation the "lines" between the two departments will over time continue to "blur." It is time for the military operations research community to address this issue and determine how best to support the analytical requirements of military forces involved in both homeland security and national defense.

As we gather for the 71st MORSS let me ask that discussion of the above challenges be addressed while we're together at Quantico. ✪