Proceedings of the 2003 Winter Simulation Conference
S. Chick, P. J. Sánchez, D. Ferrin, and D. J. Morrice, eds.

BAY OF BISCAY: EXTENSIONS INTO MODERN MILITARY ISSUES

Lance E. Champagne

Air Force Institute of Technology
Department of Operational Sciences
2950 Hobson Way
Wright-Patterson AFB, OH 45433, U.S.A.

ABSTRACT

Multi-agent simulations are finding application in an increasing number of areas over a wide spectrum of disciplines. In recent years, the application of multi-agent systems to problems in the military has received a proportional amount of interest. However, the military analysis community is in its infancy with respect to multi-agent simulations, and the efforts thus far have involved relatively simple scenarios. As a result, these efforts have not been able to bring multi-agent simulations into the mainstream of the analysis community. In this paper a mission-level agent-based simulation of the U-Boat war in the Bay of Biscay between German U-Boats and Allied aircraft is presented. The results from two 6-month intervals of the operations are presented and compared to historical outcomes. The scenario is subsequently generalized to provide a basis for extension into modern military situations of significant interest. Additionally, several relevant examples are presented.

1 INTRODUCTION

The first agent-based combat simulation to be found in the literature was a cellular automata (CA) model used to show tactics as an emergent behavior (Woodcock, Cobb, and Dockery 1988). Since then, as in many other fields of study, there has been increasing interest in the use of agent-based models for military analysis. In spite of a large and growing field of agent literature, most articles deal with cooperative agents, that is, agents with compatible goals (Hendler 1999). In this aspect, work in the area of combat simulations differs from the vast majority of agent literature.

Perhaps the most coordinated effort to date at agent-based combat simulations is the US Marine Corps' Project Albert. This effort began with the idea of exploring "the middle ground between … highly realistic models that provide little insight into basic processes and … ultra-minimalist models that strip away all but the simplest dynamical variables and leave out the most interesting real behavior" (Ilachinski 2000).

The first Project Albert simulation, Irreducible Semi-Autonomous Adaptive Combat (ISAAC), was built as a proof-of-concept model to demonstrate the applicability of complex adaptive systems (CAS) to combat modeling. Although ISAAC is often referred to as a "conceptual playground" (Ilachinski 2000; Ilachinski 1998), it and follow-on simulations such as Socrates, Pythagoras, and Map Aware Non-uniform Automata (MANA) have demonstrated promise for gaining insights into battle not possible with traditional combat models. Published results have demonstrated the potential in ISAAC-type models to contribute in diverse areas such as the development of tactics as an emergent behavior (Ilachinski 2000), exploring the role of combatants' trust in combat effectiveness (Bergeman 2001), providing risk assessment for peacekeepers, and quantifying the value of reconnaissance to combat effectiveness (Lauren 2001).

In recent years, there has been an increased number of agent-based simulations studying various aspects of combat. For example, Tighe, in (Tighe 1999), developed an agent-based simulation based ultimately on the boids flocking algorithm (Levy 1992) and ISAAC (Ilachinski 1998) as an attempt to find a method of quantifying strategic effects, purported to be one of the main strengths of air power in combat. Bullock, in (Bullock 2000), continued the research into modeling strategic effects with the introduction of the Hierarchical Interactive Theater Model (HITM). This model was intended to provide a sufficiently complex tool able to show strategic effects of air power, while retaining enough simplicity to allow identification of interactions between important factors. Other agent-based combat simulation research includes modeling riot tactics for small military units (Woodaman 2000), small unit peacekeeping tactics in an urban environment (Brown 2000), and a German training scenario involving small units over a relatively short time period (Erlenbruch 2002).

Though each of the above provides significant results toward advancing the field of agent-based combat simulation, no attempt was made to relate simulation outcome to real-world data. This paper outlines the development of an agent-based combat simulation based on the Allied offensive against the German U-Boats in the Bay of Biscay during WW II. Model results are compared to the historical data. Finally, the scenario is generalized to provide several modern contexts for similar agent-based combat simulations.

2 HISTORICAL SCENARIO

German U-Boats operated against Allied shipping in the North Atlantic from 1941 through the end of the war in an effort to reduce the shipments of war-time supplies to Great Britain. Following the fall of France, many of these submarines operated from ports in occupied France, crossing the Bay of Biscay into the North Atlantic, where they hunted for Allied transport ships. Once they left the Bay of Biscay, the U-Boats could, for all practical purposes, operate outside the reach of Allied aircraft support. For a time in 1942 and 1943, this offensive was so successful, that Great Britain's war effort was put in great peril.

While the Allied forces had little hope of finding and destroying U-Boats once they reached the Atlantic, the Bay of Biscay was well within the reach of Allied aircraft. Additionally, the amount of U-Boat traffic to and from the French ports, necessitated by maintenance and resupply/refuel demands, ultimately meant that there was sufficient density of targets within the Bay of Biscay to warrant committing resources to conduct anti-U-Boat efforts there. As a result, the Allied forces, beginning in 1941, hunted for the U-Boats in the Bay of Biscay.

Both the Allies and the Germans were able to consistently add technological advances to their forces during these operations. Additionally, as each side was able to identify their opponent's new advance, they were able to modify their own tactics or improve upon existing countermeasures to eventually mitigate the innovation. As a result, the "measure-countermeasure" seesaw of technology and tactics is prominent throughout the operations.

Additional historical background on the offensive search in the Bay of Biscay can be found in (McCue 1990), and an extensive record of the corresponding operational analysis may be found in (Waddington 1973) and (Morse and Kimball 1998).

2.1 Advantages as an Agent-Based Simulation Scenario

Operations in the Bay of Biscay benefited in large measure to the application of operations research techniques. Waddington, in (Waddington 1973), details the extensive analyses performed by Allied scientists in support of the offensive search in the bay. Additionally, McCue, in (McCue 1990), details additional analysis efforts conducted post-war and provides additional analyses of the operations in the Bay of Biscay. Therefore, there is an extensive body of data and analyses available for comparison to the methods developed in this research effort. In addition, there are characteristics of the Allied offensive search operations that make it very appealing as an application for agent-based simulation.

For example, the measure/countermeasure nature of the operations is an ideal basis for building an agent-based simulation. Perhaps just as important, although WW II does not represent cutting edge military technology, the measure/countermeasure adaptation displayed during the operations on both sides is highly demonstrative of the nature of conflict, regardless of the technology level. Therefore, principles developed through this application should be theoretically applicable to a wide range of scenarios.

Additionally, many of the measures/counter-measures used in the Bay of Biscay operations were information-based. The abilities to intercept and decrypt the opponent's communications and receive advanced warning of the enemy's proximity through radar warning receivers played an important role for both sides throughout the operations. As the DoD increases its focus on information warfare (IW), the tools developed through this simulation should be readily extendible to explore more general IW implications to combat operations.

Furthermore, the Bay of Biscay operations can be modeled initially at several different levels of combat detail. The available information suggests that the operations could be modeled both at the engagement and mission levels, the primary distinction being the duration of combat operations and the number of agents involved. Indeed, because the U-Boats had such little success in destroying attacking aircraft, the scenario bears a great deal of resemblance to a cellular automata (CA) model that has typically demonstrated theoretical importance, the predator-prey model (Boccara, Roblin, and Roger 1994). Similarly, a mission level simulation would then allow for the integration of CA-derived results to be rolled into a simulation involving a higher level of data aggregation.

Finally, the scenario surrounding the operations presents a wide range of factors that are well suited to simulation. For instance, the availability and impact of refueling U-Boats in the Atlantic, the maintenance bottleneck in the French ports, and quantity of "offensive" and "defensive" Allied searches present classic "what-if" and tradeoff analysis possibilities.

3 BAY OF BISCAY MODEL

Though the Bay of Biscay simulation was built to reproduce the results of the historical operation in both qualitative and quantitative measures, one of the development goals was to keep the simulation relatively simple by including only the most significant factors. As a result, assumptions regarding the simulated system had to be made, and the following sections detail the issues most important to the construction of the model.

3.1 Assumptions

In constructing the Bay of Biscay simulation, it was necessary to make assumptions about the environment, the aircraft agents, and the U-Boat agents. The following sections detail the primary assumptions made with respect to each of these. These assumptions represent operations and tactics from both the Allied and German perspectives as faithfully as possible without including an inordinate level of detail.

3.1.1 Environment

Both U-Boat surfacing policy and aircraft effectiveness were governed by day and night. Within the simulation, "day" is defined as the time between nautical dawn and nautical dusk (i.e. sun is above -12° with respect to the horizon). In addition, daylight computations are approximations made with respect to a single point near the geographical center of the Bay of Biscay and are applied to all locations in the simulation. This approximation is considered very good outside of the arctic and Antarctic circles (Heilman 2000), and as the Bay of Biscay lies significantly outside these regions, approximations were deemed sufficient.

The French ports used to base the U-Boats were heavily defended and protected by German air patrols. Additionally, U-Boats leaving and entering port areas had air escorts available to them. Therefore, a region extending 100 NM from the coast of France was identified in which agent behavior of both types was affected. Specific behaviors regarding this region are found in the following two sections.

All detection sensors are assumed to conform to the Inverse Cube Law, indicating that the probability of detection is inversely proportional to the cube of the distance between sensor and target. This assumption is supported by field testing performed during WW II (McCue 1990; Waddington 1973; Morse and Kimball 1998).

The Inverse Cube Law is an important assumption in that it provides a convenient closed form solution for combinations of detection sensors that conform. When more than one sensor is used, the resulting sweep width, or effective sensor range, is approximated as the square root of the sum of squared sweep widths for the individual sensors, given by (1), and specific sweep widths for independent sensors were obtained from (McCue 1990).

$$W_{total} = \sqrt{\sum_{i=1}^{n} W_i^2} \tag{1}$$

where W_i is the sweep width of the i^{th} sensor
n is the number of independent sensors.

There are two issues worth noting with respect to such sensor combination calculations. First, the approximation breaks down when the number of independent sensors, n, is increased sufficiently. For example, no combination of sensors would allow for a positive probability of detection for objects beyond the horizon. Second, the probability of detection, given by (2) (McCue 1990), provides for positive probability of detection regardless of the distance between the sensor platform and the target. Therefore, using (2), there is a positive probability (though minute) of detecting a target beyond the horizon.

$$P(x) = 1 - e^{-\frac{W^2}{4\pi x^2}} \tag{2}$$

where W is the sweep width computed by (1)
x is the distance of target-sensor separation.

Neither issue is a factor in this simulation, however. The number of independent sensors is kept quite low ($n \leq 3$), sufficiently small to avoid the first issue. To avoid making nonsensical probability checks, a random detection check is made only when a target is within the sweep width of the sensor platform ($x \leq W$). This leaves a certain (minor) amount of detection probability unaccounted for, but the savings in computation time gained, as well as avoiding nonsensical detections, warranted making this sacrifice in accuracy.

3.1.2 U-Boat Assumptions

Information governing the tactics, policies, and operation was significantly more difficult to assimilate into the simulation than for the Allied agents. Primarily, this was due to availability, but much of the available information conflicted between sources. In cases of conflicting information, especially between non-German sources, the source having the latest date of original publication was used, since typically the later studies had access to more declassified sources, both German and Allied. Therefore, the newer sources were deemed more reliable.

U-Boat agents within the simulation must spend a minimum of 3 hours surfaced for each 100 nautical miles (NM) traveled to fully recharge their batteries. This accounts for the fact that the U-Boats involved in the Bay of Biscay operation were not outfitted with the snorkel, developed very late in the war, which would allow them to operate with their diesel engines while submerged. Therefore, within the simulation, all U-Boat agents are simulating battery operation while submerged and diesel operation while surfaced. Additionally, U-Boat movement is 10 knots (NM/hour) surfaced and 2.5 knots submerged.

U-Boats travel to and from port via a shortest path. This accounts for Allied sources indicating U-Boat travel was essentially East-West within the Bay of Biscay (McCue 1990; Waddington 1973).

U-Boats leave port with 30 days of supplies and return from operations in the North Atlantic so as to arrive back in port with no supplies remaining. Additionally, U-Boat refueling at sea is implicitly accomplished by allowing a 0.25 probability of extending their time in the North Atlantic by 30 days. This fraction of the operational fleet includes the common practice of commanders extending their operational tour to 60 days by stretching their initial resources (McCue 1990; Morse and Kimball 1998).

Throughout the war, anti-aircraft artillery from the U-Boats was wholly ineffective. Therefore, it was generally German policy to submerge when Allied aircraft were sighted. Likewise, U-Boat agents in the simulation will submerge immediately upon detecting an aircraft, regardless of their battery recharge state. Once submerged, these agents will travel submerged until their battery level is depleted. The relationship between time on the surface and level of battery charge is assumed linear, so while three hours surfaced would allow for 100 NM underwater, 1.5 hours surfaced would enable the agent to travel 50 NM. Upon battery depletion, the U-Boat agent would coordinate the timing of its surfacing to coincide with its surfacing policy (i.e. day or night). Regardless of surfacing policy, the U-Boats in the simulation operated in a surfaced state while they were in the region of the environment protected by German air patrols.

Perhaps the biggest unknown factor regarding U-Boat activity concerned the time spent in port, and this remains the biggest unknown regarding the link between the Bay of Biscay simulation and the real-world operation. There was simply not enough data available to support anything but an educated, reasoned guess. In the simulation, U-Boats time in port is given as a random variable between 25-40 days, inclusive. This is derived from (Morse and Kimball 1998) which states that the average time a U-Boat would spend "about 30 days" in a port operating under its capacity (no strict queuing argument is attached to the word capacity in this instance). However, from other sources, most notably (McCue 1990), the French ports were often choked beyond their ability to service all the boats at any given time, especially toward the end of the war when German resources became scarce.

3.1.3 Aircraft Assumptions

Over the Bay of Biscay, Allied aircraft were able to act with impunity, and German U-Boats had ineffective active defenses (i.e. anti-aircraft artillery). While there were undoubtedly accidents involving the loss of aircraft over the length of the campaign, the offensive search for U-Boats constituted a small force of aircraft, and the available fleet used for this purpose was not impacted by such occurrences. As a result, there is no attrition due to accident or anti-aircraft defenses within the simulation.

Likewise, the aircraft agents in the simulation will standoff from the coast of France to avoid enemy air patrols and escorts. Agents will not enter the port region except for one situation; if an aircraft locates a U-Boat prior to the U-Boat entering this region, the aircraft will follow the U-Boat into the region and attack it. Following the attack, the aircraft will immediately exit the region.

Aircraft agents move at a constant speed of 120 knots, and the effects of weather once a mission is launched are not simulated. Once airborne, each aircraft will fly up to 70% of its fuel load or until it has expended its munitions. This fuel factor is supported by subsequent analysis (Waddington 1973) in spite of policy indicating pilots were to fly up to 80% of their initial fuel capacity.

Simulated aircraft are able to detect only surfaced U-Boats. Once spotted, an aircraft will pursue the U-Boat until the attack is made, to the exclusion of all other considerations. In attacking a U-Boat, the aircraft agent will expend its entire payload of munitions and return immediately to its base.

Weather and maintenance problems were a big issue with respect to successful Allied operations, and they are accounted for in the model through random draws. At the beginning of each simulated day, a random draw is made to determine if the weather is sufficient for Allied missions, and a draw indicating poor weather grounds the entire fleet for the day. Maintenance, on the other hand, affects aircraft agents individually and is determined immediately prior to take-off. Once in the air, agents are not afflicted with poor weather or maintenance problems that would force a mission abort, and aircraft will return to base only for fuel or munitions.

Aircraft agent search was concentrated in a search zone covering the heart of the Bay of Biscay measuring 200 NM x 350 NM. Figure 1 shows the entire search zone in relation to the Bay of Biscay. Figure 2 isolates this search zone and show the 50 x 50 NM^2 search grids used by individual aircraft.

Figure 1: Search Area in the Bay of Biscay

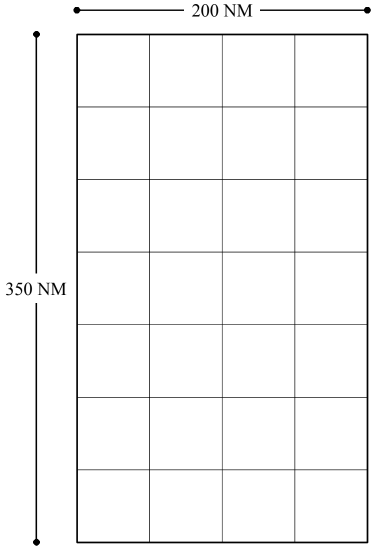

Figure 2: Search Grid Used by Aircraft Agents

The search zone, in turn, was divided into non-overlapping search grids measuring 50 NM x 50 NM (Figures 2 and 3). Each aircraft in the simulation was assigned to a specific grid in which to search for U-Boat agents.

WW II operations researchers determined that the approach angle optimizing the chance for locating a U-Boat traveling on the surface of the water was a 45° angle (Waddington 1973). Since the U-Boats were assumed to be moving East-West (E-W), searching aircraft would employ SE NW or NE SW search lines as much as possible. To this end, a modified barrier search pattern was simulated for search within each grid (Figure 3). Moreover, the pattern was repeated until the agent either sighted a U-Boat or reached a critical fuel level. Based on the size of the search grid, this allows multiple passes through the pattern, even for grids most remote from the aircraft base.

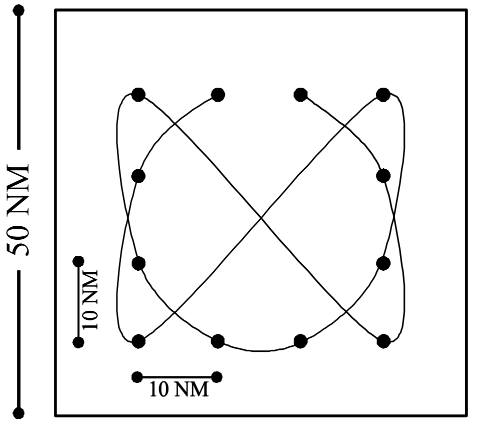

Figure 3: Modified Barrier Search Pattern

While the actual size of the grid was arbitrary, the agent behavior while searching conforms to historical accounts (Waddington 1973). Additionally, the search zone concept, if not the exact sizes and locations, simulates the historical record.

3.2 Simulation Scenarios

Two scenarios were chosen for the initial exploration. The first was the six month period from October 1942 – March 1943 (Scenario 1), and the second was April 1943 – September 1943 (Scenario 2). These time periods were chosen because the technologies used by both Allied aircraft and German U-Boats remained relatively constant over the months within each, although they did vary significantly between scenarios.

The U-Boat fleet initially consists of 70 agents distributed randomly and uniformly throughout the Bay of Biscay. When each replication begins, half the fleet move toward the North Atlantic, and half move toward their home port. There are five home ports located on the coast of France, and the agents are evenly assigned among them.

A simulation warm up period of 12 months is used to position the fleet, through normal movement through the bay and time spent in operational zones and ports, in a more natural configuration as might have been the real-world case. U-Boat fleet reinforcements begin arriving from Germany according to their historical numbers (McCue 1990) in month 11 of the warm up period and continue throughout the remainder of the simulation.

The aircraft fleet consists of 15 agents in Scenario 1 and 35 agents in Scenario 2, collocated at a single airbase in Great Britain. These numbers were derived through experimenting with the two scenarios until the average monthly flying hours compared favorably with the historical values. The number of aircraft agents remains constant throughout each scenario simulated. Though the aircraft conduct missions throughout the simulation, they are prevented from searching for the U-Boats during the simulation warm up period.

Aircraft offensive search is assigned to a fixed area of the bay 200 x 350 NM^2 (E-W x N-S; see Figure 1). The search area is subdivided into 50 x 50 NM^2 non-overlapping grids (Figure 1). Aircraft search each grid according to a modified barrier search pattern constructed from the tactics discussed in (Waddington 1973; see Figure 2). In addition, the aircraft search for U-Boats during ingress to and egress from their assigned search area.

Each scenario was replicated 20 times, and statistics were kept for the 6-month total and on a per-month basis.

4 SIMULATION RESULTS

Combat simulations, unlike many real-world processes, tend to be singular in nature. That is, there are not multiple occurrences to hypothesize a distribution. Engagement models tend to be of this nature due to their relatively short duration.

Output from the simulation are compared to the two primary measures of effectiveness (MOEs) from the real world data, number of U-Boats sighted and number of U-Boats sunk.

4.1 Analysis of the Simulations MOEs

Table 1 shows the actual and simulated mean over 20 simulation runs for both MOEs of interest.

Table 1. Simulation vs. Historical Results

	Scenario 1		Scenario 2	
MOE	Actual	Sim Avg	Actual	Sim Avg
Sighting	135	154.2	319	333.5
Kills	3	3.2	32	32.1

Joint confidence intervals around the simulation means can then be constructed using a t-statistic, shown in (3).

$$Bound = \bar{x} \pm \frac{s}{\sqrt{n}} \cdot t_{\frac{\alpha}{2\cdot k}, n-1} \qquad (3)$$

where

- $\bar{x}$ is the sample mean
- s is the sample standard deviation
- n is the sample size
- k is the number of joint confidence intervals
- (1 – α) is the desired level of joint confidence.

Selecting a (1 – α) = 0.8, consistent with simulation validation literature (Balci and Sargent 1984; Balci 1994; Kleijnen 1995), confidence intervals were constructed around the simulation means for each scenario assuming a t-distribution with 19 degrees of freedom. The 80% joint confidence is maintained for each scenario. That is, if 80% confidence were desired over both scenarios considered together, then the confidence intervals would need to be extended.

Figure 4 shows the results from scenario 1, and the results from scenario 2 are shown in Figure 5. In each case, the confidence intervals either cover or nearly cover the MOE's historical value.

Supposing that the actual number of sightings and kills represent the mean of the true distribution for each scenario, then the joint confidence intervals shown in Figure 3 and Figure 4 would indicate that the simulation does a reasonable job of emulating the scenarios and statistically captures (or nearly captures) the actual values observed during WW II.

Though the results appear to indicate the simulation is a good statistical representation of the historical scenario, two points bear consideration. First, the joint confidence level encompassing both scenarios guarantees a (1 – α) significantly less than 0.8. Second, this conclusion is derived from the assumption that the historical record is representative of the mean of all possible outcomes from the real-world scenario and not a statistical outlier – a decidedly risky assumption. Since there is no way of knowing whether or not this assumption is valid given a "sample size of one," conclusions as to the validity of the model should still be considered suspect. However, as a preliminary assessment, the model appears to represent the historical record satisfactorily, and the statistical tests do not contradict this.

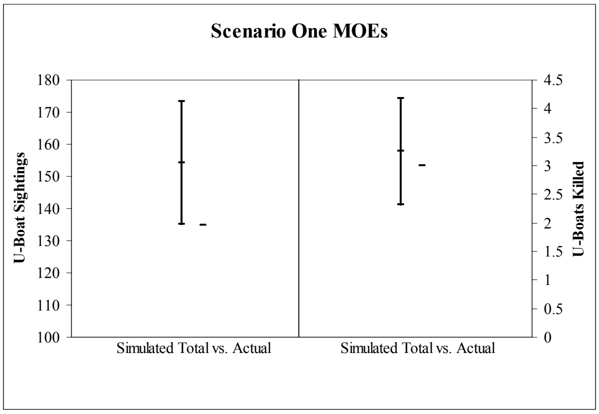

Figure 4: October 1942 – March 1943 MOEs

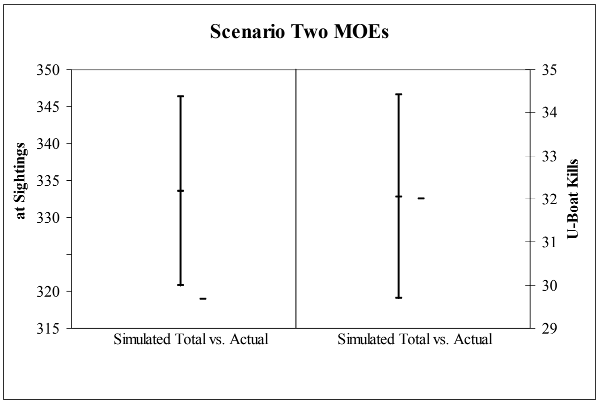

Figure 5: April 1943 – September 1943 MOEs

5 SCENARIO GENERALIZATION

In the more than sixty years since the Bay of Biscay campaign took place, technological advancement has made the simulated scenario inapplicable to modern submarine/anti submarine operations. Modern nuclear submarines do not need to surface for extraordinarily extended periods of time, stay out of port for many months of continuous operation, and are able to travel much deeper and more silently than was possible during WW II. As a result, search by air is generally an ineffective proposition. In spite of this, the basis for the Bay of Biscay scenario can be widely applied to current operations. Some of these operations extend beyond military application into the realm of law enforcement, immigration, treaty verification, arms inspection and others.

5.1 Scenario Fundamentals

The properties underlying the offensive search for U-Boats in the Bay of Biscay suggest that other situations may be investigated with similar agent-based tools. Because of the nature of these situations, the discussion will be from the viewpoint of the searching party.

One of the primary characteristics of the Bay of Biscay scenario is that the target is not known to be in the search zone. Fundamentally, this aspect varies from the majority of the modern literature on search methods, which typically assume one or more targets to be within the search zone. Though the target is known to pass through the search area, there are an unknown number of targets in the region at any given time.

Although the area of origin and area of operation are well known to the searchers, these areas are beyond their influence, so action against the targets is severely constrained at the point of origin and operation and is effectively possible only when the target is in transit between its origin and operational zone. Moreover, it is known that the target must pass through the search zone to get to its operating zone, and it must pass through it again on its way back to its origin point.

The target is mobile, and while in transit, the target is uncooperative (in search terminology this means the target is not willing to be found and is actively working to avoid detection). However, while the target is uncooperative, it is visible and vulnerable to detection, at least for short time periods.

Finally, the search assets come from outside the search area. These assets are limited in number and capability, and as a result, they are not always in the search zone.

6 APPLICATION TO MODERN SCENARIOS

Though this research is no longer applicable to anti-submarine operations, there are modern applications which have similar characteristics to the simulated scenario. Several of these are discussed below.

6.1 Terrorist Identification and Interdiction

One of the more recent scenarios to which this type of agent-based simulation may be able to provide insights is that of terrorist interdiction. Since terrorists most often do not wear uniforms, they are not visible as terrorists until they are in the process of a hostile act, and once they reach their operation zone, it is often too late to prevent their mission from being at least partially carried out. Therefore, the opportunity to identify and interdict them must be while in transit. This is perhaps most applicable to the Israelis, who share a controlled border with the typical terrorist population.

6.2 Treaty Verification (SCUD Hunting)

Though treaty verification differs somewhat from the previous example, it is sufficiently similar to indicate that agent-based simulation may be applicable. In the case of a banned, but deployable, weapon system such as the SCUD missile in Iraq, the weapon system can be hidden or made to blend in with other equipment, but when deployed, the system is vulnerable to detection. Since the system has a limited range, search can be limited to areas from where launches would most likely occur to strike probable targets. Again, limited search assets are available and must be mobile to “catch” the system when it is deployed.

This application is particularly interesting in the context of the Bay of Biscay simulation as well. Finding SCUD missiles has been a significant political objective since the first Gulf War, and as a result, it has received a considerable amount of consideration within the military community. The notion of applying anti-submarine warfare (ASW) principles to finding SCUD missiles was proposed in (Wirtz 1997) and (Connor 1997), and successful application to ASW in the Bay of Biscay simulation suggests that the techniques of agent-based simulation could be extended to the problem of locating SCUD missiles as well.

6.3 Mobile Chemical Weapons Production Facilities

Like the previous example, offensive search for mobile chemical weapons production facilities differs from that of the Bay of Biscay, but there are sufficient similarities to indicate an agent-based approach may provide insights.

Mobile chemical weapons production facilities are virtually impossible to find and identify when not in production mode. However, when producing the chemical or biological agents, the facility must be stationary, and there are particularly well identifiable support equipment that must be present. Therefore, while the processing is ongoing, the facility is vulnerable to detection. Additionally, these facilities must be within range of delivering their products to capable handling facilities (Powell 2003). Therefore, a probable search area can be determined for extremely limited search assets within a hostile environment.

Though the preceding examples are not the only scenarios that have the above characteristics, these are some that are directly concerned with national security and have been of recent widespread interest.

7 CONCLUSIONS

Though agent-based combat simulations have generally concentrated on relatively simple scenarios, the Bay of Biscay simulation presented in this paper models a mission-level scenario with an agent-based construct. Moreover, the results indicate the model was capable of reproducing historical outcomes for two scenarios covering six months each.

Though the successful application of an agent-based approach to mission-level combat scenarios is significant, the technologies of the Bay of Biscay scenario make the anti-submarine warfare aspects hopelessly dated. However, this does not exclude usefulness in relevant military scenarios. Once the scenario has been generalized, it bears significant resemblance to several important national security related issues.

ACKNOWLEDGMENTS

This research was funded by the Defense Modeling and Simulation Office (DMSO) and the Air Force Research Laboratory, Human Effectiveness Directorate (AFRL/HES).

REFERENCES

Balci, Osman and Robert G. Sargent. 1984. Validation of simulation models via simultaneous confidence intervals. *American Journal of Mathematical and Management Sciences*, 4: 375-406.

Balci, Osman. 1994. Validation, verification, and testing throughout the life cycle of a simulation study. *Annals of Operation Research*, 54: 121-174.

Bergeman, Russell. 2001. Considering the intangibles: identifying social capital in military units. *Maneuver Warfare Science 2001*, ed. Gary Horne and Mary Leonardi. Quantico, VA: Defense Automated Printing Service:.

Boccara, N., O. Roblin, & M. Roger. 1994. Automata network predator-prey model with pursuit and evasion. *Physical Review E*, 50: 4531-4541.

Brown, Lloyd. 2000. Agent based simulation as an exploratory tool in the study of the human dimension of combat. Monterey, CA: Naval Postgraduate School.

Bullock, Kelly. 2000. Hierarchical interactive theater model (HITM). WPAFB, OH: Air Force Institute of Technology. AFIT/GOA/ENS/00M-05.

Connor, George. 1997. A commentary. *Airpower Journal*, XI: 97-98. Montgomery, AL: Air University.

Erlenbruch, Thomas. 2002. Agent-based simulation of German peacekeeping operations for units up to platoon level. Monterey, CA: Naval Postgraduate School.

Heilman, Brian. 2000. Sunrise-sunset calculations <`http://www.codeproject.com/datetime/srss.asp`> [accessed August 2002]

Hendler, James. 1999. Making sense out of agents. *Intelligent Systems*, 14: 32-37.

Ilachinski, Andrew. 1998. Irreducible semi-autonomous adaptive combat (ISAAC)," *Maneuver Warfare Science 1998*. ed. F.G. Hoffman and Gary Horne. United States Marine Corps.

Ilachinski, Andy. 2000. Irreducible semi-autonomous adaptive combat (ISAAC): an artificial life approach to land combat," *Military Operations Research*, 5: 29-46.

Kleijnen, Jack P. C. 1995. Statistical validation of simulation models. *European Journal of Operational Research*, 87: 21-34.

Lauren, Michael. 2001. Applications of a distillation to questions for the New Zealand army," *Maneuver Warfare Science 2001*. ed. Gary Horne and Mary Leonardi. Quantico, VA: Defense Automated Printing Service.

Levy, Steven. 1992. *Artificial life: a report from the frontier where computers meet biology*. New York: Vintage Books, a division of Random House, Inc.

McCue, Brian. 1990. *U-boats in the Bay of Biscay: an essay in operations research*. Washington DC: National Defense University Press.

Morse, Philip M. and George E. Kimball. 1998. *Methods of Operations Research*. Alexandria, Virginia: Military Operation Research Society. Reprinted in its entirety from © 1951 first edition printed by MIT Press and John Wiley & Sons, Inc.

Powell, Colin. 2003. Transcript of Remarks to the United Nations Security Council. New York, New York. February 5, 2003. <`http://www.state.gov/secretary/rm/2003/17300.htm`> [accessed April 2003]

Tighe, Thomas. 1999. Strategic effects of airpower and complex adaptive agents: an initial investigation. WPAFB, OH: Air Force Institute of Technology. AFIT/GOA/ENS/99M-09.

Waddington, C. H. 1973. *O.R. in world war 2: operational research against the u-boat*. London, England: Paul Elek (Scientific Books) Ltd.

Wirtz, James A. 1997. A joint idea: an antisubmarine warfare approach to theater missile defense. *Airpower Journal*, XI: 86-95. Montgomery, AL: Air University.

Woodaman, Ronald. 2000. Agent-based simulation of military operations other than war small unit. Monterey, CA: Naval Postgraduate School.

Woodcock, A. E. R., Loren Cobb, and John Dockery. 1988. Cellular automata: a new method for battlefield simulation. *Signal*, 42: 41-50.

AUTHOR BIOGRAPHY

LANCE E. CHAMPAGNE is a Major in the United States Air Force and a Ph.D. student within the Department of Operational Sciences, Air Force Institute of Technology.

He has B.S. degrees in Mathematics and Biomedical Engineering from Tulane University and an M.S. in Operational Sciences from AFIT. His research interests include agent-based modeling and verification and validation methodology. His email address is <`lance.champagne@afit.edu`>.

Distribution: DISTRIBUTION A. Approved for public release; distribution unlimited.

Disclaimer: The views expressed in this article are those of the authors and do not reflect the official policy of the United States Air Force, Department of Defense, or the US Government.