SEMI-AUTOMATED FORCES: A BEHAVIORAL MODELING APPROACH

Hung T. Le, Ph.D.
Stephen E. Phinney
Vernon C. Seward

IBM Corporation, 9500 Godwin Drive, Manassas, Virginia 22110

Abstract *-- This paper briefly reviews the problems and challenges faced by training communities in providing a realistic opponent for tactical training in a battlefield environment. A functional model for simulating semiautomated forces (SAFOR) is defined. Behavioral modeling using a motor schema approach is introduced for adversarial planning and navigation. A mathematical formulation using ellipsoid model is described. This is followed by a scenario developed for battlefield planning to reflect the applicability of motor schema instantiations for controlling semiautonomous agents.*

1. INTRODUCTION

With today's increasingly complex tactical environment, innovative solutions to the associated problems of training will be required to prepare combat team readiness. This entails emulating opposing force and friendly force units to support combat training of battalion level armor units that include a network of manned vehicle simulators. In a battlefield training environment, these emulated forces must be deployed on a simulated battlefield in accordance with an established military doctrine. Training also requires effective control of emulated forces that incorporates the capability to direct emulated force tactics and movements across simulated terrain in order to conduct force combat engagements with other simulated units.

In light of the very complex nature of modern warfare, the requirements to effectively train military personnel, in many situations, stipulate a large number of entities to take part in a wargaming scenario. Using fully manned simulators, however, in a large force would be too costly in terms of equipment and human resources usage. In addition, it would be extremely difficult to find personnel who may be familiar with enemy doctrine and tactics to provide crews for manned enemy vehicle simulators. Thus, to alleviate the need for the full complement of a battle force and the role playing opposing forces (knowledgeable in enemy tactics) in a war-gaming environment, some research and development work has been initiated to build intelligent simulators that are capable of generating friendly as well as opposing forces, known as semi-automated forces (SAFOR), in a wide range of complex operational settings. While these research and development work is aimed at addressing problems in battle planning using artificial intelligence techniques, the environmental model has often been assumed static, and the sole application of expert system to automated battle planning is not sufficient to meet real time requirements for battlefield training environment. Problems in mission planning using optimal search techniques also do not lend themselves to real time applications. These shortfalls result in SAFOR systems that are highly constrained in their behavioral characteristics, and thus cannot adapt to emerging situations or changing environments as required in a realistic battlefield setting.

In this paper, we adapt a motor schema-based model, which describes the interaction between perception and action, to address problems in automated adversarial planning that provide active and reactive mechanisms for controlling semiautonomous agents. SAFOR's behavioral modeling concept with its functional elements will be presented in section 2. In section 2.1, a motor schema based approach will be introduced. This is followed by a mathematical formulation of ellipsoid models in section 2.2. Using this framework, we will discuss aspects of agent modeling, environmental modeling and group behavior in the context of adversarial planning in section 2.3. A number of features of the navigation code are given in section 3.

2. BEHAVIORAL MODELING

The goal of SAFOR modeling is to develop both the ability to simulate collective behavior of combatant agents to succeed in simulated battle engagements while requiring each agent to exhibit unique behavior and react to local terrain and battle conditions. Force simulation models currently tend to only model statistically collective behavior. This approach is weak in application such as some anti-submarine warfare problems as well as in this application where the number of trainees and/or simulated combattants is undetermined. The approach used will result in an autonomous agent that can exhibit "local" behavior. The agent is linked to other autonomous agents via links emulating the actual human-technology link between agents in a real battlefield situation.

A suitable simulation requires interchangeability between a human "operator" controlling the simulation agent and replacing the operator with an autonomous simulation. This approach allows the construction of engagement scenarios for the training of operator crews (i.e. tank tactics training) or evaluation of new equipment capabilities and tactics. To accomplish this, three aspects of the simulation are described below: the agent or combatant unit, the connection of these units into a coordinated group, and the governing environment in which the units operate.

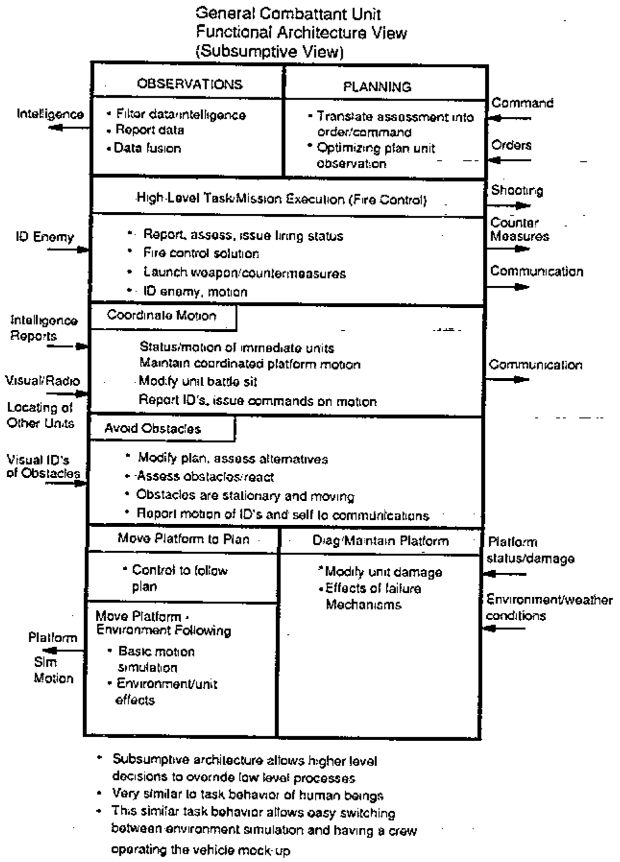

FIGURE 1. FUNCTIONAL MODEL OF A GENERAL COMBATANT UNIT

The primary objective, then, is not only to emulate the behavior of a real agent but to develop a general functional model whose instantiation can be used to simulate a variety of combatants from infantry and tanks, to submarines and sonobouys. In this way, this SAFOR approach can be the basis of a tank battle engagement. The major functional elements of this agent are shown in Figure 1. The functional elements, basic vehicle control (move the unit according to a plan and maintain the unit), obstacle avoidance, motion coordination with cooperating agents, military mission/engagement, and intelligence/planning are arranged in a hierarchical manner similar to a subsumptive approach (Brooks, 1988). The difficulty of using a pure subsumptive approach is that it only solves the reactive role of the agent whereas in our constrained simulation, our sensor world is ideal, behavior is sometimes dictated by a context driven tactic and overall objectives or plans to be met. This requires adapting the functional hierarchy to a task oriented approach similar to the one used by Shudy (1988). The agent simulation fulfills many of the tasks found in autonomous robot control systems (UNH for NEODTC, 1990).

The agent or combatant unit does not require a full robotic approach. The SAFOR environment is only a simulation with deterministic events in which few unexpected events can occur. Agent movements in the SAFOR environment also assume that terrain knowledge, gained from maps and multiple agent communications in the real battle environment, is common to the multiple agent simulation. This more easily constrains the planning function and simplifies path planning and execution.

The basis of the agent motion is a motor schema based model which models the unit's dynamical behavior based on the resolution of velocity potentials selectively applied to the agent at any one time. This requires the environment to be characterized by attractive/ repulsive potentials and unique feature designations to simulate the agent navigation around obstacles and react to snow, fog, visibility in day or night conditions, or follow a road. The higher level functions which are based on higher reasoning and plan execution will selectively override or modify the motor schema forces. These functions implemented as distributed processes will better apportion the processing loading.

To address interactions between multiple agents, the group behavior we are developing is based on the simulation of normal communications paths which exist in a battle force between cooperative units. Within the hierarchical military command, orders are disseminated "down" the command chain. Plan decomposition from the highest level to the lowest level produces collective behavior consistent with the overall expected results. Plans are based on externally imposed objectives, a defined environment, and perceived knowledge of the enemy configuration. Perceived *knowledge is the result of fusing the individual unit* perceptions up the chain of command to the highest level. Each simulated combatant, sensor unit, or commander can be represented by instantiating an agent. By moving intelligence "up" the communications link, passing plans "down" the link and using a common "Map"/ environment, the resultant group behavior will cooperate for a mission success. Likewise, the disruption of these knowledge sources will potentially cause a disruption in cooperative mission success. Hence realistic scenarios in the simulation are realized.

2.1 MOTOR SCHEMA APPROACH

The term "motor schema", originated in the fields of psychology and neurology, defines a generic specification of a computing agent. In other words, this concept of behavior represents an individual's response to its environment wherein each schema models a generic behavior. In this framework, the instantiations of these generic schemas provide the potential actions for the control of the computing agent.

The behaviors of an agent are represented by a set of schemas generated as artificial fields whereby actions and reactions are guided. Basically, an artificial potential is a mathematical description of the potential energy which may act upon an entity within a given environment. The potential may be associated with natural or man made entities at rest or in motion. *Artificial potentials may be* divided into two types: attractive and repulsive potentials. For each detected obstacle and/or region of threat, a modeled repulsive field is assigned. Likewise, a modeled attractive field is assigned for each target or objective on the battefield. These forces cause an entity to move through the environment in a manner directly responsive to the modeled velocity function of that environment. For autonomous navigation, attractive potentials may be assigned to objectives and repulsive potentials to obstacles to guide an entities navigation across a specified area. Thus, an entity may be directed to autonomously navigate toward a tactical or strategic objective while avoiding natural and man made obstacles of a moving and stationary nature.

In our problem, the motor schema model is used to determine the sequence of actions for achieving a set of military objectives. In this model, agents' behavior is be defined based on the velocity fields set up around obstacles and/or regions of high threats. To cope with the associated uncertainty with perception in the battlefield environments, a probabilistic mechanism is built into the velocity field generation. As the perceptual mechanism's confidence (activation level) exceeds a predefined threshold for action, a repulsive (attractive) field is set up to surround the obstacle (target). The intensity of repulsive force is affected by the distance from the semiautonomous agents and the obstacle's perceptual certainty. Furthermore, the field strength may also depend on the type of mission, and *therefore, can be set up accordingly.*

The above described approach will provide the system with an ability to adjust plan dynamically during plan execution, as required in a dynamically operational environment with low predictability. Schema modeling also allows a large number of semiautonomous forces to be controlled simultaneously, and semiautonomous agents' behavior to be directed toward cooperative actions in a dynamic battlefield environment. Furthermore, with the use of schema models, some elements of stochastic behavior (random actions) are introduced, and therefore, agents' behavior will not be predictable. In addition, this approach also provides an effective way to model objects in the simulated terrain as well as potential fields, which gives rise to a very efficient algorithm.

2.2 SCHEMA GENERATION USING ELLIPSOID MODELS

2.2.1 ELLIPSOID MODELS

Any given object in the battlefield environment, whether stationary or moving, is represented by a set of ellipses (see for example, Yegenoglu et. al. [1988]) denoted as a region of points enclosed by the contour $\| \Phi_0 \| = C$, where C is a positive scaling factor. In this formulation, the vector $\Phi_0(X)$ is defined as

$$\Phi_0(X) = -[\nabla H_0(X)]^{-1} H_0(X) ,$$

and

$$H_0(X) = \begin{pmatrix} (\alpha_{11}x_1 + \alpha_{12}x_2 + \beta_1)^{\sigma} \\ (\alpha_{21}x_1 + \alpha_{22}x_2 + \beta_2) \end{pmatrix},$$

where, $\alpha_{11}x_1 + \alpha_{12}x_2 + \beta_1 = 0$ defines the minor axis and $\alpha_{21}x_1 + \alpha_{22}x_2 + \beta_2 = 0$ defines the major axis of the ellipse. The lengths of the minor and major axes of the ellipse are given as 2C and $2\sigma C$, respectively.

To establish velocity fields for any target or obstacle, we require that: (1) the field be smooth and differentiable for smooth trajectories and constrained accelerations; (2) the field should point away from or tangential to the obstacle near obstacle boundaries; (3) outside the vicinity of an obstacle, the field should point toward a target; (4) the field must not contain any local minima; (5) the field should approach zero at the target boundary; and (6) the field should be additive to handle multiple contacts. To account for requirement (4), an "escape" velocity must be added to the field vector resulting from the interactions among fields contributed by targets and obstacles. The vector field can be then be computed as a linear combination of the attraction and repulsion vector fields. The resultant vector, which gives the directional force acted on the vehicle, is *given as follows:*

$$V(X) = \frac{\Psi(X)}{|\Psi(X)|} \left\{ v \left(1 - e^{-b_a D_a(x)} \right) \right\}$$

where,

$$\Psi(X) = \Psi_a(X) + \Psi_r(X)$$

$$\Psi_a(X) = \frac{\Phi_a(X)}{\gamma_a D_a(X) \, \| \Phi_a(X) \|}$$

$$\Psi_r(X) = -\sum_{i=1}^{s} \frac{\Phi_{r_i}(X)}{\gamma_{r_i} D_{r_i}(X) \, \| \Phi_{r_i}(X) \|} e^{-b_i D_{r_i}(X)}$$

v is the velocity of the vehicle, s is the number of obstacles in the field of view, b_a and b_i are spatial repulsion decay rates, D_a and D_{r_i} are the distances to the target "a" and obstacle r_i, respectively. γ_a gives the class entropy for the set of attractors, and γ_{r_i} gives the class entropy for the ith *set of repellers* (Yegenoglu *et* al. [1988]). This implementation provides a means to cope with the associated uncertainty with perception in the battlefield environments.

The escape velocity can be computed as:

$$V_e = K_e \, e^{-b_e |\Psi(X)|} \, \eta(X) ,$$

where $\eta(X)$ is the unit vector perpendicular to $\Psi_r(X)$. The resulting vector can then be calculated as:

$$V_T(X) = V(X) + V_e(X).$$

2.3 PLANNING

2.3.1 Agent Modeling

The functional model for an agent or combatant unit, as shown in figure 1, depicts five behavioral layers required for the simulation of an independent agent. They are layered from the most fundamental tasks up to the most complex. Although this is the same notion as Brooks (1986) subsumptive architecture, this approach as a more constrained reactive schema (i.e. motor schema) vice reactive responses to blindly perceived obstacles. Imbedded in this model is the planning of a tactical response required by a military combatant.

The lowest level controls the agent in a constant motion. The motion is modified according to locally imbedded features (i.e. mud, fog, slopes). Overriding this behavior may be the constraint to follow a road or path. *This constraint allows following* a road even if it abuts an obstacle which could have a high repulsive potential. Also at this level, the agent readiness subfunction determines degradation due to equipment failure or firepower damage. Remaining energy resources, for examples fuel, battery, and so on, are evaluated and used by the planning function as a mission "cost".

The second level uses the motor schema model to selectively choose obstacles and modify the motion to avoid these obstacles. In addition, because these course changes deviate from the original plan, a secondary plan is invoked to negotiate the agent back to the original plan, if possible. The motor schema model is also suited to perform this task. The identification of the motion of other "observed" agents and the motion of this agent is communicated to the next command level. This data, modified for simulated uncertainties, form the basis of data to be fused with other data at higher command levels.

The third level handles cooperative or group motion. This function executes group plans and controls the agent motion based on positions dictated by the group commander. The command levels maintain status on the cooperative agents and adapts their plans based on the changing motion of the individual agents in the group.

The fourth level encompasses the actual military mission outside the agents simulated ability to move about the terrain. This function contains the battle/engagement strategy and the control to simulate weapon firing. Even though these tasks are functional at a high level, the need for reactive behavior during battle requires a similar implementation as the reactive obstacle avoidance under the motor schema approach.

The fifth level contains the "links" to the rest of the cooperative agents and the support processes. The planning function translates assessments or intelligence into orders at a high command level or translates low level orders into detailed action plans. The optimization of the plan for adapting to the agent's local environment is undertaken. The assessment or intelligence requires fusing agent contact information received from various agents and adapting the result to top level plan generation.

The functions and subfunctions included in this agent model can be instantiated, in some part, to most agents encountered in coordinated military operations. For example, the entire structure is used to simulate a tank. A mortar or sonobuoy requires some of the functions. The mortar's functionality is contained in the mission function and the sonobuoy's functionality is contained in the "Observations" or "Intelligence Gathering".

2.3.2 Environmental Modeling

The environment is set up as a generating function. The parameters imbedded in the representation of the terrain or ocean area are used to *constrain* the behavior of simulated agents. These parameters also serve as the basis for generating visual displays which are used in a trainer simulation where operators can replace an agent's simulation. The area is tesselated or segmented into regular geometric shapes such as squares. Each segmented area has characteristics assigned to it. The attractive or repulsive potential use in the motor schema modeling is associated with an area. This concept allows local constraints to be 'available' for an agent when it enters the area of the neighborhood of an area. Examples of these parameters are the local slope an agent must climb over or a small river bed the agent crosses over. Likewise day/night, fog, mud, snow, and rain are imbedded parameters that can be picked up by the agent when he enters the area and used to modify his behavior. An additional imbedded set of parameters relate to the 'cost' of travel across this segment or the threat weapon coverage . The cost parameters can be used to discriminate areas which are better or worse to travel over by modifying potentials in the motor schema model or aid in the decomposition of the strategic plan into detailed actions. Some of these parameters can change by themselves (i.e. day to night). In a highly parallel architecture, implementing the cells as cellular automata suggests efficient ways to manage the changing environment.

The terrain irregularities that the agent can drive over are part of the tesselated terrain whose irregularities an agent can't cross over but must go around become a terrain obstacle. These obstacles can be hills, rocks, or even rivers. The obstacles will be simulated as forms of elliptical repulsive velocity potentials.

2.3.3 Group Behavior

2.3.3.1 Cooperative Motion

The next level of challenge beyond a single agent successfully navigating the terrain is to simulate a cooperative motion among agents. The goal in agent cooperation is to coordinate the motion of many agents to result in the successful execution of a group plan. This coordination is dictated by communications from commanders down the command hierarchy. A typical arrangement of a group of cooperative agents is moving within an ellipse. By setting up a potential about a lead agent which is a neutral potential with a boundary potential wall, the agents within the elliptical wall will move in the direction and speed commanded by the lead agent as well as navigate locally avoiding collision with other cooperating agents. This elliptical wall defines the "influence" from an agent. It is sufficient for higher levels of command to know that his agents are with an elliptical boundary and not necessarily where each are specifically located. A statistical assessment is sufficient. This treatment of cooperative motion is consistent with the planning each level of command and how course or fine his knowledge of the distribution of his commanded agents is.

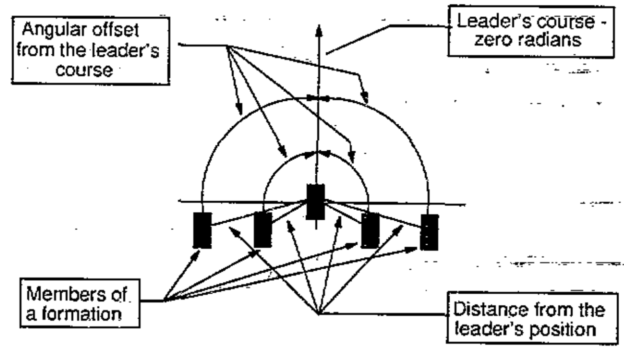

FIGURE 2. COOPERATIVE MOTION

Within the ellipse, each member agent is commanded to maintain a position consistent with a position vector assigned to it by the lead or commanding agent (figure 2). Agents or vehicles following a formation also follow the configuration dictated by the appropriate position vector. Agents avoid collision with other members of the group because each is an independent agent with his influence region creating reactive plan modifications.

Another approach to implement a march in formation is depicted in Figure 3. A formation is represented as a template in which the position of each vehicle is defined as an attractor. In this configuration, when vehicles have to break formation to avoid a moving (or stationary) obstacle, the attractors will force the vehicles back to their original locations. The force, which acted on any one vehicle, is a function of the distance from its original position. The farther the vehicle is away from its formation template, the faster it will move toward it until it gets back in formation, where the force (acceleration) acted on the vehicle will decrease to zero.

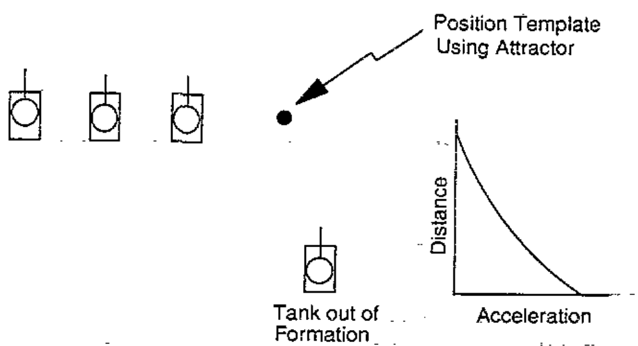

FIGURE 3. REGROUP IN FORMATION

Figure 4 shows an example scenario of cooperative agents moving along a road imbedded in the environment. It is expected that because each agent determines its minute-to-minute reactive behavior, the influence potential drop-off near the agent will produce traffic jams and grid-lock as we see on today's major metropolitan highways as more and more agents are crowded on the road. Other agents not a part of the cooperative group will be treated as moving obstacle, friend or foe, which the member agents must individually decide whether to outrun the obstacle or wait for its passing before resuming the original cooperative motion plan.

- Vehicle A has mountain, road, and vehicles B and C in field of view; plan says: follow road --> ignore mountain, avoid vehicles B and C.
- Vehicle B has road in filed of view; plan says: Follow road --> carry on as planned.

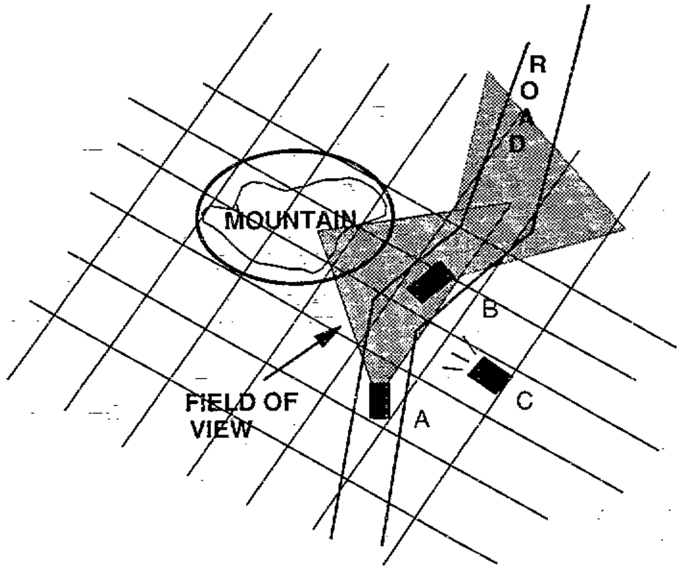

FIGURE 4. EXAMPLE SCENARIO

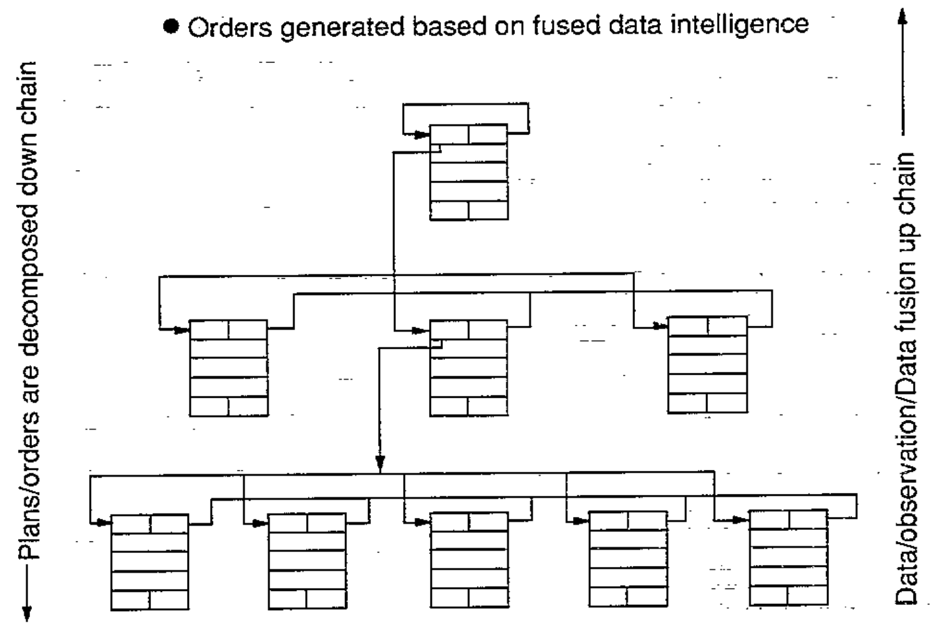

FIGURE 5. COMMAND/COMMUNICATION FOR GROUP LINKING OF COMBATANT UNITS

2.3.3.2 Hierarchical linking

The total command structure where each cooperating agent is linked by simulated communications to the others is shown in figure 5. In the figure, each agent is represented by a symbolic function diagram (figure 1). Messages are passed up the communications link which is the intelligence from each low level agent being fused and interpreted as it moves up the chain. At the top level, the simulated command officers take the intelligence, evaluate it against the plan, and generate new orders. These orders are disseminated down the command chain. At each lower level, the orders are further decomposed into detailed plans for the lowest level agent. To reinforce cooperative motion, each simulated agent has a terrain knowledge because in the real world, each combatant has a map. The particular simulation of these communication paths correspond to radio nets, or even sonar links in an underwater environment.

3. Implementation of Navigation Algorithm

To demonstrate the overall concept, the Moving Platform System (MPS) developed at the Naval Postgraduate School (Zyda et al., 1989) is used as a simulator testbed to conduct performance study of the motor schema-based approach as applied to navigation. The MPS provides a good vehicle to experiment with the navigation algorithm in that it allows for the creation and control of several types of vehicles on a simulated terrain.

In this implementation, some of the features that are added to the MPS as a mean to facilitate man-machine interface controls for demonstrating the navigation code are:

- The ability to select the repulsive field strength for each vehicle. Field strength is measured by how close an opposing vehicle will get before its course is affected. Four repulsive field strengths are currently provided, 1 kilometer, 1/2 kilometer, 1/4 kilometer and 0 kilometer or no field.

- Selecting whether a vehicle will 'sense' another vehicle's repulsive field. This feature will allow a vehicle to have a field but be oblivious to other fields.

- Providing multiple targets for each vehicle. This feature allows each vehicle to have a list of targets independent of each other. Multiple targets allow each vehicle to have a 'mission' that can include moving to several positions. Once the final target is reached the vehicle stops.

- A formation can be created with any combination of vehicles and in any position. Any vehicle within a group can be selected as a formation leader. If this option is selected, each subsequent vehicle generated will be a member of the formation.

With the navigation algorithm in place, autonomous control of numerous vehicles can be realized. Obstacle avoidance is achieved by establishing repulsive field around objects (threat regions, moving or static obstacles) in the simulation. The autonomous vehicles sense the strength of the fields and turn away when the field strength reaches a predefined level. An attractive field can also be generated for specifying a target toward which the vehicle is steered. The combination of attractive and repulsive field produce a vector on which the vehicle will steer while moving through the simulated environment.

4. SUMMARY

In this paper, we presented a motor schema based approach to modeling SAFOR's behavior. Using a subsumptive architecture, we developed a hierarchical structure for SAFOR that exhibits major functional elements of a combattant unit. These functional elements include basic vehicle control, obstacle avoidance, motion coordination with cooperating agents, military mission/engagement, and intelligence and planning. Within the very levels in SAFOR's hierarchical structure, we illustrated the applicability of the motor schema approach in basic navigation, cooperative or group motion in battle march using ellipsoid model, and low-level planning in a battle engagement scenario.

5. REFERENCES

Brooks, R. (1986), "A robot layered control system for a mobile robot," IEEE Journal of Robots and Automation, RA-1.(1), pp. 1-10.

Semet, H., Fujimura, K., (1988), *Path planning among moving obstacles using spatial indexing,* Chapter 1, pp.1662-7.

Shudy, R., Duarte, C. (1990) Advanced autonomous underwater vehicle software architecture.

Yegenoglu, F. and Stephanou, E. H. (1988), "Real-time obstacle avoidance in dynamic environments," to appear in IEEE Transactions on Automatic Control.

Zyda, J. M., Fichten, A. M., and Jennings, H. D. (1989), "Graphics workstations and 3D visual simulation: Some performance expectations and measurements," Technical Report NPS52-89-046, Monterey, California: Department of Computer Science, Naval Postgraduate School.

UNH for Naval Explosive Ordinance Disposal Technology Center (April 1990). Systems/Subsystems investigation for a multisensor.

Autonomous Underwater Vehicle Search System. Final Report NAVEODTECHCEN technical report TR-301.

6. BIOGRAPHIES

Dr. Hung T. Le has been involved in the research and development of image processing algorithms for underwater acoustics applications. More recently, he has been working in research and development of AI/Expert systems for training.

He has published numerous papers in the areas of statistical signal processing and artificial intelligence. He currently serves as an adjunct professor in the department of Operations Research and Statistics at George Mason University.

Dr. Le is a member of Tau Beta Pi, Eta Kappa Nu, the Institute of Electrical and Electronics Engineering, the Operations Research Society of America, and the American Statistical Association.

Stephen E. Phinney received a B.S. in Physics at the University of Rochester, New York in 1964. He is an Advisory Systems Engineer for IBM, Federal Sector Division, Manassas, Va. He has been developing signal processing and system architecture requirements for submarine sonar and combat systems for AN/BQQ-5, Trident, and AN/BSY-1 combat systems. He was responsible for Sonar Trainer design and environmental simulations. More recently, he has been responsible for site AI technology introduction. He is involved in research and development of AI/ Expert systems for training and control systems for AUVs and robotics. In addition, he is involved in the development of expert systems diagnostic applications in Naval systems development and operational environments.

Vernon C. Seward has been working as a programmer in linguistic and office systems applications with the Application Solutions Division at IBM Bethesda, Maryland, since 1989. He is currently conducting research and development of Artificial Intelligence systems in training and simulation. His responsibilities include design and development of AI algorithms for tactical training systems.