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THESIS

**REALISTIC EVALUATION OF TERRAIN BY
INTELLIGENT NATURAL AGENTS (RETINA)**

by

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September 2003

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REALISTIC EVALUATION OF TERRAIN BY INTELLIGENT NATURAL AGENTS (RETINA)

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ABSTRACT

US Army and Joint constructive simulations require human operators to observe the exercise in progress, conduct analysis of the results, and provide a realistic reports and assessment of the action presented on their screens to the desired training audience. Current software tools provide excellent mathematical assessments (such as center of mass calculations, optimal routes, and sensor ranges) but poor human-like assessment of data (most likely route, probable enemy intention, etc.).

This Thesis presents an artificial intelligence architecture specifically designed to reduce that manpower requirement by describing a concept for computer modeling that can produce realistic human-like assessment results. Specific concepts described are approaches for conducting a digital terrain assessment, development of avenues of approach, deployment of templated forces to a specific piece of terrain, and then a method of adjusting the templated force to react to actual sightings and known information.

Also included are more detailed discussions and implementation details for use of gas diffusion as a method of analyzing avenues of approach through digital terrain. This approach seems quite promising as a method of modeling human movement tendencies and appears superior to classic path finding or optimal route selection methods.

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I. INTRODUCTION

A. THESIS STATEMENT

It is possible to create a very realistic military assessment of terrain and digitally represented forces using a combination of agent-based programming and computer vision techniques to array templated forces on digital terrain, and using a fluid flow model to develop likely avenues of approach through the terrain.

B. MOTIVATION AND OVERVIEW

United States Army simulation exercises are conducted by three categories of people: the training audience (military commanders and staffs receiving primary benefit from the simulation exercise); the technical support staff (largely civilian, these are the installation support personnel who runs the simulation computers and networks); and the training enablers (military personnel, normally from one echelon below and above the training audience). The motivation for this thesis is the training enablers. Those soldiers primary duty is to read information on a computer screen and relay it to the training audience in a believable manner which preserves the integrity of a "real" or simulated real event rather than raw data from a computer printout. These soldiers perform a "sanity check" on simulation truth presented to them on their screens and then report a version of assessed truth to the training audience. This is a valuable function, without which military training simulations would be very difficult, or very unrealistic. The price in manpower, however, is quite high. For some exercises the training enablers outnumber the training audience as the Army strives to provide the most realistic training possible for its warfighting staffs. This thesis is an attempt to reduce the required size of the training enablers by exporting some of their current duties to an artificially intelligent system which is able to see digital terrain, recognize militarily likely avenues of approach, and template defensive positions on the terrain based on some tactical planning heuristics and computer vision deployment principles.

C. THESIS ORGANIZATION

The main contribution of this thesis is intended to be its description of methods for taking raw, linear data (digital elevations, specific vehicle locations, etc.) and providing the singularly human aspects of analysis and assessment to produce value-

based comments such as "most likely," "probable," and "best estimate." In military staff organizations one of the most subjective functions is that of the intelligence analyst who must piece together high volumes of data to produce a coherent picture of the terrain and of the enemy – both his actions and his intentions. This thesis attempts to mirror a number of these functions in software, and as such borrows freely from current U.S. Army Intelligence doctrine and training for both the structure and content of the thesis.

The organization of this thesis loosely parallels the U.S. Army's Intelligence Preparation of the Battlefield (IPB) process. In general, this process consists of a structured approach of analyzing terrain by military value and trafficability, applying general friendly and enemy movement and deployment tendencies to the terrain to produce estimates of most likely (and most dangerous) actions or deployments, establishing a collection plan to gather confirming (or denying) data at specific locations of interest, and then adjusting the templated positions to correspond to reports of known positions or actions.

1. Seeing the Terrain

Although rich terrain database information is available for some parts of the world, particularly those of military interest, this work assumes that only elevation data is available, though richer terrain data could be easily included in the described approach. In the most basic sense, the military aspects of terrain are dominated by two major factors: the direct fire line of sight at any given point; and the vehicular maneuverability at any given point. Protection, observation, cover, concealment, obscuration, key terrain, and other terrain factors are, in the opinion of the author, secondary to the more basic considerations of which forces I can engage with my direct-fire weapons systems; and where the enemy is going to be. This issue perhaps deserves more detailed treatment, but for purposes of this thesis will remain as unproven assumption. In this section we discuss how the agent-based programming methodology led to a requirement to classify terrain by military value based on mobility factors and briefly compare the preferred by-cell approach versus use of mobility corridors or bands of high density line of sight vulnerability. The implemented software approach makes use of the standard, three-tiered military terrain classification (Go, No Go, and Slow Go), but lends itself to

multiple classifications of terrain classification and is extensible to much richer terrain database information.

2. Assessing the Terrain

Intelligence officers and military terrain experts classify terrain in decidedly non-linear terms. They use phrases such as "high speed avenues of approach," "most likely defensive positions," "slow mobility corridors" and other terms which assign an order of value or merit to certain terrain features. In order to conduct a human-like assessment of terrain, we first needed to quantify the terrain with some sort of value. Defensively, the value of any given piece of terrain is relative to many factors – location of other defensive units, weapons system range and capabilities, location of planned or desired engagement areas, and expected location of enemy forces. Of these factors, however, foremost is expected enemy location, for this leads to description of engagement areas, around which defensive units are deployed based on other rules for dispersion and massed effects. Offensively, terrain value is based on the ease with which one can traverse a portion of terrain enroute to a particular objective. Given this, the foremost source of terrain "value" for both offensive and defensive calculations is the ability of a military force to traverse that piece of terrain enroute to an objective. This section contains a detailed description of an implemented software approach for developing realistic military avenues of approach through terrain using a modified gas diffusion model. This original method produces intuitively natural human movement tendencies that: can be easily converted to value elements based on speed of movement, proximity to ideal route, or other heuristics; closely rival optimal path-finding approaches in efficiency; and are extensible across an entire terrain sector for use by goal-seeking agents in search of ideal terrain.

3. Deploying Forces on the Terrain

Deploying military forces on terrain is an exercise in modifying the most appropriate general pattern, or "doctrinal template" of forces to suit the particular terrain selected for the fight. This method of matching specific environmental cues to the most appropriate general pattern is similarly discussed in both Army Intelligence School training documents, in artificial intelligence research and papers discussing computer vision, and in naturalistic human decision-making research. The parallels between these

three areas provide the basis for the most promising method of deploying templated defensive forces on terrain given certain cues. Foremost among those cues are the military value of terrain, discussed earlier, and what can be loosely described as the central defensive point or anchor point around which the defense is to be deployed. This section discusses an agent-based deployment approach to specific positioning preceded by two approaches for selecting the central defensive anchor points, one based on a purely mathematical evaluation of attacking force vulnerability, and the preferred approach which borrows from gradient concentrations in the gas diffusion model. These heuristics are discussed as concept with only initial level software implementation complete at time of this thesis, but did compare favorably with results obtained from military terrain experts in a related experiment.

4. Adjusting to Respond to Reports of Actual Sighted Vehicles

This section continues the theme of pattern-based recognition and details a concept for using computer vision techniques to compare expected disposition of forces with reports of actual vehicles. Templated forces are deployed on the digital terrain based on both a macro-assessment of avenues of approach and movement objectives but also based on successively lower resolution views of the specific nature of the surrounding terrain based on echelon of deployment. We consider each echelon of deployed force as its own pattern, within which subordinate elements have both a prescribed general pattern as well as some flexibility of adjustment within the parameters of that pattern. Adjustment is accepted and expected at each level of resolution within certain constraints. Reports of vehicles sighted, then, are compared to summaries of lower-level patterns (and their associated probabilities) to see if the general nature of the pattern as a whole will allow the specific nature of the reported vehicle(s) within the constraints of the current pattern. If not, the pattern at that level is adjusted to better fit the reported vehicles and the process is repeated for the next higher echelon. This section includes a discussion of this method as well as mention of how these techniques can be applied to infer current and future intent with varying levels of confidence.

D. GENERAL SCENARIO

All of the digital terrain files for this thesis are Digital Terrain Elevation Data (DTED) Level II from publicly available elevation data about the U.S. Army's National

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Training Center at Fort Irwin, California. Tactical scenarios assume an East to West attack of a mechanized force from the boundaries of Fort Irwin towards the buildings of Fort Irwin proper. When deploying forces, I've assumed one mechanized Infantry battalion task force-sized organization to defend against a regimental-sized mechanized enemy force. None of the parameters of this data are limited to this particular data set, however, and should apply equally well to other data sets of widely varying scope and resolution.

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II. RELATED WORK AND BACKGROUND

A. INTRODUCTION

The Panel on Modeling Human Behavior and Command Decision Making: Representations for Military Simulations, Commission on Behavioral and Social Sciences and Education, National Research Council, concluded its 1998 report as follows

> The modeling of cognition and action by individuals and groups is quite possibly the most difficult task humans have yet undertaken. Developments in this area are still in their infancy….Human behavior representation is critical for the military services as they expand their reliance on the outputs from models and simulations for their activities in management, decision making, and training.

Given the scope of this effort, the majority of this chapter will remain at a fairly high level of detail, assuming that the reader is conversant in the essential elements of each subject heading. From a global point of view, this thesis should not be classified as completely new work but as a new combination of existing artificial intelligence and computer science techniques applied to a troublesome problem domain to achieve a new solution. As described in Chapter I, the problem domain is achieving a human-like assessment of military unit predisposition on a given set of digital terrain and a continuously updated evaluation of military unit intentions on that terrain given partial and incomplete information. Researchers throughout the world have contributed to the various aspects of this approach, so for brevity I've tried to only include the specific works which provided direct insight to the selected approach or which summarize alternate methods of achieving similar results. Related work is discussed below; separated by subject area into Terrain Assessment and Path Finding, Military Deployment Heuristics, Agent-Based Modeling, Computer Vision, and Naturalistic Decision Making.

B. TERRAIN ASSESSMENT, PATH-FINDING AND ROUTE SELECTION

Having read a digital terrain elevation file for basic terrain sample, we face the problem of describing the terrain by mobility characteristic and then traversing this terrain sample by most realistic method possible to obtain likely avenues of approach.

Many researchers have tackled these issues; a data search for published path finding articles will yield several thousand.

1. Mechanical Methods

The majority of these articles discuss variations on what I will call mechanical methods of path selection; methods computed based purely on the mathematics of the terrain set without regard for how humans truly navigate. De Berg and O'Rourke both discuss methods of motion planning for robots or other automated planning tools which utilize shortest path techniques for navigating an obstacle field. Included in their discussions are approaches for smoothing out the irregularities on an obstacle's face by use of convex hulls and of expanding obstacle dimensions by the size of our moving element (such as a robot) to ensure that the passing object can traverse the shortest path. Other approaches discussed in these works involve use of shortest path obtained by computing edge-to-edge line of sight to produce a tree of straight line segments followed by an A* search (Norvig) to produce an optimal path. These approaches would all result in a group of valid potential routes through a sector, but there is no indication that they would represent the routes that a human (or a group of humans) would use to traverse that sector.

Powell implements a combination of Delaunay decomposition and Theissen triangulation to produce mobility corridors which are essentially the curvilinear routes between all NoGo terrain sectors. Once computed, these mobility corridors are assigned weighted values for width and length which can be used to produce cost factors for searching.

Reece discusses advantages and disadvantages of motion planning by cell decomposition (modified A* search for least cost), skeletons (obstacles expanded to create single path between each obstacle), weighted regions based on threat exposure, and potential functions by distance from objective and proximity to obstacles. Of special interest to this thesis is Reece's assertion that using a potential field algorithm can result in local minima which could trap the algorithm unless obstacles are weighted with negative potential values to "push" the paths away or unless one considers velocity (Krogh). This is because the potential field Reece discusses is not a fluid-like potential based on movement from a source to a sink but a mathematical potential computed by

distance from the sink and avoiding obstacles. Potential fields computed purely based on distance to goal and avoidance of obstacles can fail to produce desirable results because of their lack of a global view. A potential field generated by diffusion equations at a state near equilibrium cannot produce dead ends as every gradient vector points towards the strongest path to the sink. This is discussed in much more depth in subsequent chapters.

Reece implements a limited scope A* search to evaluate the node-to-node movement cost based on time to complete with slope and mobility factors included as costs. Following this, the results are post-processed to reduce turns, increase speed over open areas, and adjust movement postures (i.e. Standing to Prone) to reduce overall cost. Reece's approach is not implemented in this thesis for several reasons. First, it assumes a purely mathematical approach to human movement and route selection based on optimal search criteria. Optimal routes through terrain are perhaps appropriate for computing individual movement, but are not good representations of the larger scale military movement tendencies we needed to model for this thesis. Secondly, Reece's node-to-node A* search and post processing technique does not lend itself well to large scale terrain models required to evaluate movement of forces across a potentially large terrain file. Though computing diffusion is similarly cycle intensive, we believe that there are efficiencies possible in a diffusion approach which make it more attractive for large databases. Finally, Reece does not make an argument for extension of this pathfinding algorithm to a broader scale classification of avenues of approach based on likelihood of use (which is the requirement for this thesis), and it is unclear how his approach could be modified for that particular task.

Horn implements a similar line of sight approach to route selection, though he does include other constraints into his cost factors to account for gradient, distance, and concealment.

Forbus reads in a bitmap file to produce a Go/NoGo grid from commercial game terrain maps, then demonstrates an algorithm which combines skeletonization and cell decomposition to produce tubes and open space for more efficient search algorithms. A similar approach (producing skeletons and open areas) is suggested in this thesis as a

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means of reducing the A* search pattern required when comparing the NoGo/Go chokepoints for possible defensive positioning with mechanical methods.

Benton describes an approach for use in computing terrain grid searches over extremely large databases by first generating a binary Go/NoGo map, thinning the map, converting it to a graph, simplifying the graph, computing paths between each node in the graph, and then computing total costs from start to end. Once computed, optimal paths are released from the requirement to specifically traverse nodes which results in more gradual route segments and some additional efficiency. Benton further develops this algorithm by conducting multiple improvements to increase efficiency of his A* search trees and reduce searches to a more reasonable number of trees and branches than the million data points he envisions in the abstract. Similar to Reece, Benton also dismisses potential approaches to path finding in his survey of other relevant work as being likely to produce local optima from which the algorithm cannot escape. Again, this is attributable to the difference between a static potential (to the objective and away from obstacles) versus a moving flow (with the origination point as source).

2. Human Movement and Extension

Duckham's work on simplest paths proposes that humans prefer a simplest path algorithm to optimal path selection. He proposes a simplest path algorithm designed to reduce the number of turns, stops, and general degree of difficulty in navigating an urban environment to create routes which appear more natural and human-like than some of the shortest path algorithms would produce. Duckham states that further cognitive studies are required to verify the algorithm but concludes that this approach appears to present considerable advantages due to ease of description and navigation. Duckham's assertion, that easier routes are preferred, is in line with military terrain analysis which emphasizes consideration of planning factors such as natural lines of drift, path of least resistance, and easiest route. Other researchers have noted similar human tendencies to drift, or move along routes with curved behaviors that consider the effects of velocity, turning radius, and speed (Brogan).

In 1746 Maupertuis developed the Principle of Least Action to describe the tendency of elements in nature to seek the minimum effort solution. Euler expanded upon this principle in 1748 with his assertion that a system of bodies at rest will seek a

state which minimizes total potential energy, or effort. This principle, is reflected in the physical property Geodesy. To quote Davis, from his website:

> Geodesy, as the term is used in physics, is the tendency of physical changes and processes to take the easiest or minimal path. Almost the whole of physics can be represented in geodetic form. Water running downhill seeks the steepest descent, the quickest way down, and water running into a basin, even one with irregular shape and bottom, distributes itself so that its surface is as low as possible, the water then has the minimum potential energy in the earth's gravitational field. Light finds the quickest trajectory through an optical system (Fermat's principle of Least Time). The path of a body in a gravitational field (i.e. free fall in space time) is a geodesic. Feynman's formulation of quantum mechanics is based on a least-action principle, using path integrals. Maxwell's equations can be derived as conditions of least action. Newton's mechanics is contained in Hamilton's principle of least action, and also Gauss's principle of least constraint. Thomson's theorem states that electrically charged particles arrange themselves so as to have the least energy. The Second Law of Thermodynamics requires that thermal systems change along a sequence of configurations, each having a higher probability of occurrence than the preceding configuration.

This thesis implements the assumption that this principle (Geodesy) can also be applied to human route planning and path selection. Without benefit of cognitive studies to confirm (or refute) this assumption, this work implements a fluid-based simulation approach to modeling human movement tendencies when selecting avenues of approach through a terrain sample.

3. Fluid Mechanics and Potential Fields

The concept of using fluids to represent human movement tendencies arose out of discussions on how best to model a moving, multi-vehicle element. These discussions repeatedly involved the use of fluid-like terms to describe the properties of a moving unit which led to the search for simple fluid models. Rather than delve into the detailed Navier-Stokes equations discussed in the textbooks (Chorin), we turned towards a simpler solution for creating the same results. Stam provided an efficient method of simulating movement in gas and smoke fields for use in visual simulations. Stam's simplified version of the Navier-Stokes gas exchange equations were instrumental in achieving the fluid simulation approach utilized in this thesis.

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The idea of using exchange and diffusion equations to model movement axes closely mirrors previous work in using potential fields to provide robotic pathfinding logic. Connolly proposed using Laplace equations as method of obtaining robotic pathfinding without the disadvantage of local optima. He defines a potential gradient for each cell based on the Laplace equations for each of its four neighbors. The solution of the Laplace equation is a harmonic function which is able to achieve the goal without getting stuck in local optima. In Connolly's second paper he discusses use of harmonic functions as method for robotic control, which, as he says

> …can be used to generate smooth, collision-free paths without the threat of spurious local minima.

Svenson presents a similar implementation to this thesis in his paper utilizing agents (ANTS) which move from the enemy location in a uniform fashion until achieving success by attaining a goal states which are the friendly unit locations. Once successful, the ANT leaves a scent along his route which other ants can follow to achieve similar success and the result of these movements is a potential field based on scent of each particular goal state. Svenson points out that this method can be used to develop avenues of approach as well by computing an exact potential based on every cell rather than the minimized potential derived by exchanges only along the ant paths. This exact potential calculation is very similar to the cell-by-cell fluid exchange we utilize in the following chapters, and yields a similar potential field for each cell. Svenson correctly points out that achieving convergence is time-consuming for the exact method and implements a reduced grid search with his ants. One could apply this same methodology to a RETINA-generated product by reducing (or coarsening) the terrain set. Coarsening is discussed later, along with some of the problems inherent with using a reduced grid to develop global strategies. A minor point, but one worth noting, is that Svenson's description of avenues of approach is more consistent with what I would refer to as areas of high gradient concentration, or areas of high potential. In order to actually generate avenues of approach one must populate the gradient field (or potential field that the ANTS produce) with an element which traverses the potential field based on the combined effects of the local potential vectors. The avenues of approach shown in Svenson's paper are, in the author's opinion, more accurately described as areas of high potential.

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C. DEPLOYMENT HEURISTICS AND RULE BASED SYSTEMS

Department of the Army Field Manuals (FM) 100-61 and 100-63 provide a rich source of doctrinal templates suitable for converting into the general templates used in this thesis. Similarly, FM 34-101, Intelligence Preparation of the Battlefield, provides a comprehensive view of the procedures employed to produce an evaluated application of a doctrinal template to a specific piece of terrain. This is a complex process, however, which does not lend itself to a single solution. As such, this thesis proposes a system of linked methods, spatial reasoning, and military heuristics to present solutions in the challenging domain of creating human-like military reasoning for artificially intelligent software.

Other researchers have attacked this problem with similar conclusions (about the degree of difficulty) and levels of resolution. Richbourg's paper addresses the issue of military deployments on terrain as a similar combination of AI search and military heuristics. He searches for points of good visibility based on limited sample search and then further restricts the results to those locations sufficient in size to support his defensive positioning and with moderate slopes. He uses a visibility analysis to produce probable attack routes, assuming that the attacking force will seek to maintain concealed routes to the objective using a best first search technique through a terrain grid of visible/concealed sectors. Richbourg deploys platoons with a combination of spatial reasoning techniques, military tactical heuristics, and application of a platoon deployment pattern consisting of three squad locations, a security plan, an obstacle plan, observers, and a platoon intelligence plan. Line of sight calculations dominate deployment planning at several levels, albeit calculated for a reduced set of points. Clearly, Richbourg's approach produces a more thorough treatment of a platoon defensive planning metric than applied in this thesis. We implement a simpler set of defensive deployments based on a requirement to produce flexible plans that support a wider variety of deployment echelons over much larger terrain samples, and to do so in real time.

RETINA's avenue of approach analysis lends itself to broader applications than Richbourg's method which is primarily based on line of sight visibility from a variety of potential defensive positions (and which assumes the attacking force both knows the defending forces' locations and selects routes primarily based on their ability to support

unobserved movement). Though our methods for employing specific planning heuristics, positioning, and path selection differ, as well as the scope of research efforts, I nonetheless wholeheartedly concur with Richbourg's concluding statements shown below.

> No single heuristic, rule-based paradigm, spatial reasoning technique, or other approach in isolation has proven sufficiently powerful to provide acceptable results in this domain….Many simple techniques, applied in proper scope and role, together provide a synergy that can successfully address a difficult problem and result in a system that has application in diverse domains, succeeding where past attempts, founded on sciences from more traditional fields, have failed.

Burger's READ-PRO is a company-level program which executes direct line of sight calculations by reading DTED data and using the MODSAF line of sight algorithm. READ-PRO is designed to assist a ground force commander in positioning vehicles and targets for maximum engagement area coverage, but was not extended for use by RETINA due to our requirement to conduct a simpler, faster analysis of a much larger terrain set.

Janiszewski tackles this problem from a completely opposite direction, devising a rule-based system to evaluate potential courses of action to be executed inside of a constructive simulation, then using the post-processing files from that simulation to evaluate the success of his system. Human users input a number of rules, indicators, and assessments into the expert system which then monitored the simulation results and provided an assessment to the training audience. While not directly related to this thesis, I found the approach to be helpful in demonstrating both the scope of effort involved in this process as well as reinforcing the requirement for (substantial) future work aligning actions with intent. This alignment must naturally follow from a knowledge or belief about the current truth of enemy disposition on the terrain. In his conclusion Janiszewski states

> …If the rules and rule sets are not broad enough to assess potential OPFOR COAs, then the assessment…will have little value to a commander. Likewise, while the cognitive process that an S2 uses to make an assessment can be without flaw, if the information to make that assessment is unavailable, then the reliability of that assessment can be at best questionable. …care must be taken to collect that information. The

plan used to place intelligence collection assets on the battlefield, referred to as the collection plan, must be completely thought through with the anticipated enemy courses of action in mind..

Before we can predict intent we must know position. RETINA's bottom up approach is based on the author's opinion that the most important aspect of understanding enemy intentions are to first ensure that we've achieved a full understanding of the environment on which he will operate.

D. COMPUTER VISION

Computer vision is an approach to model and encode for use by a computer the physical processes which occur when humans see and recognize objects. These processes are well described by Kandel in his Neural Science textbook, but in general terms the eye contains detectors which become activated upon seeing a familiar pattern. We recognize edges on objects because they excite receptors in our visual cortex which are only excited when seeing an edge pattern. In digital terms, this is roughly equivalent to a binary pattern such as the one shown below.

0	1	0
0	1	0
0	1	0
0	1	0

Table 1. Binary Equivalent of Edge Detectors in the Visual Cortex.

These cells become stimulated when the "1" cells from the simple table above align with the dark line of an observed edge. This basic principle is the genesis for most of the binary image recognition and sensing discussed in Horn's treatment of robot vision, and the computer vision texts by Ballard and by Forsyth. Ballard's discussion of template recognition where each template is visualized as connected to the others by a series of imagined springs is an illustrative metaphor for the methods we'll use in RETINA to construct higher level deployment templates

Yen's discussion of fuzzy logic for use in robot pathfinding and pattern recognitions is an example of the type of scaled confidence approach required to implement the links between cues and inference into actually being able to reasonably determine intent. Similarly interesting work involving fuzzy logic, Bayesian belief networks and sensor fusion (combining the reports of multiple sensors to present one

"fused" report) is described by Gonsalves, as is an extension of this method combined with a genetic algorithm to produce potential high level of abstraction enemy courses of action (COA) and then a rough means of assessing the utility of these COAs. Gonsalves (and subsequent work by Das) describe a structured implementation of initial research with belief networks for situation assessment via belief networks. This majority of this work is conducted at a very high level of abstraction and could be extended downward to consider specific terrain factors. For my thesis I used the opposite approach, first considering the terrain and then building up from there to evaluate potential COAs.

Intille's description of structured multi-agent pattern recognition based on relaxed Bayesian belief networks is intriguing. Not pursued in this thesis given the fluid nature of our force size, its conceivable that Intille's approach for recognizing football plays could be applied to a military domain given modifications to accommodate for unknown size of the observed force. Once the force has been observed and classified, for example an attacking enemy whose size and disposition are known, it seems that extending this work would provide an attractive method of recognizing some of the higher resolution intent parameters.

E. AGENT BASED MODELING

A literature search for agent based modeling and simulation tools today will yield thousands of applications in almost every domain. For this thesis, agents are assumed to be reactive agents as described by Wooldridge with the ability to communicate, cooperate, and achieve local optima by form of local information searches as part of the larger group.   Numerous papers describe similar applications of highest gradient hill climbing (HGHC) to achieve the "best possible" solution for each agent based on the information he has at any given time. Orichel used a reactive agent-based system to consider route movement along a network grid of changing values and locally known information to achieve delivery from source to sink at least cost over the changing network. Hennings used a bracketing heuristic and internal agent computation of locally known distances to evaluate human and agent-based behavior. Many other theses and papers (Back, Tyler, Das, Gonsalves, Garrabrants, Schlabach, Hill, etc…) demonstrate the viability of using multiagent simulations to improve realism and training capabilities, and it is assumed that the reader appreciates the principles described in this section of the

thesis to be within common practice of goal seeking behavior of representative agents for each echelon of military unit.

F.   NATURALISTIC DECISION MAKING

In his excellent book, "Sources of Power: How Humans Make Decisions," Dr. Gary Klein presents evidence that decision makers do not make conscious choices about alternative solutions to potential problems over 80% of the time. Rather, they recognize cues in the situation based in large part on their level of expertise and then directly match the nearest appropriate "pattern" or template which fits those cues…often without even considering other alternatives. The decision maker gathers cues, recognizes a pattern or other template which seems to fit a portion of this problem, conducts a quick mental "simulation" (or estimate of success), and then executes the decided-upon plan.

Dr. Klein further expands on the degree of success enjoyed by experts in a given field by showing how experts suffer minimal decrease in good decision making even under extreme time pressure. He also points out that experts are extremely skillful in recognizing when the cues which caused them to select a course of action no longer lead towards the original conclusion. Experts are able to self-correct and select new courses of action faster than normal people because they're more in tune with "how things ought to play out.." – kind of a forward simulation of not just the plan but also the input cues which will confirm that the plan is enroute to a successful conclusion.

This thesis roughly parallels the expert decision making process described by Klein. Our expert (system) gathers information, projects that information forward, conducts an assessment of the rough value for possible employment with that information, and then makes a decision. Once the decision is implemented, RETINA continues to monitor for cues to confirm or deny the identified most likely deployment and adjusts the course of action when the cues no longer add up to a believable score. Its perhaps a stretch to claim that this process is fully implemented in RETINA, as a significant portion is conceptual discussion, but the author is convinced that Klein's work on intuition, experts, cues, mental simulation, and continuous monitoring is exactly the right solution for designing a complex system able to produce a realistic human assessment.

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III.   ARCHITECTURE

A.   OVERVIEW

This thesis is organized in sequential fashion so as to describe the linear process which begins with reading a digital elevation file and concludes with an intelligent agent producing updated assessments of tactical situations.   Practically, however, the architecture was designed from back to front.   In order to recognize and perform a human-like assessment of an enemy forces' status and intentions I first needed to be able to recognize the current situation and compare it to a previous (or hypothetical) situation. In order to represent tactical changes in a military simulation, I needed a method of comparing a given deployment status (a combination of both known and templated enemy vehicle positions) with a changed status that reflected the latest incoming situation reports and position updates.   This piece of the problem required a method of comparing state data given some reasonable probability of deviation and led to selection of a Bayesian approach to adjudicating incoming data as it varied from the current templated (or known) state. The current state is selected by means of a computer vision approach of kernel comparison at several echelons of military task organization.

In order for this kernel approach to work, I needed to have standard military deployment patterns, as well as a mathematical method of describing those deployment patterns.   My research indicated that one effective method of describing those deployment patterns was as a series of competing goals for each element of the military organization.   Using goal-seeking agent-based programming techniques as described previously, I was able to effectively adjust from a base position in order to produce deployment patterns which considered several competing military considerations.   This approach, however, depended upon additional terrain data not readily available from our digital elevation file.

Producing a goal-seeking program for optimal deployment required some additional terrain classification data. Specifically, I needed to know where the primary engagement area should be located and what would be the key terrain in the view of the defending force. In plainer terms, I needed to know: 1) where are the good places for a

defending enemy force to engage a moving or attacking force, and 2) what places on the ground require the attacking force to slow down, squeeze through, or become more vulnerable to being stopped and attacked? To solve these requirements I developed a defensive deployment heuristic method for selecting an anchor point, and identified a further need to analyze likely human movement patterns through terrain. If we know where people are likely to go, then it's a small step backward to classify this as favorable engagement area terrain when we program our goal-seeking agents.

In order to evaluate human movement patterns through terrain, I needed a way to classify "natural" movement patterns. This led to evaluation of fluid-based simulations, from which evolved the currently favored gas diffusion method of evaluating movement through a terrain file for best routes and areas of highest congestion and vulnerability. In order to accurately reflect movement through a portion of terrain I needed to reflect the physical nature of that terrain (its DTED elevation) as well the speed of passage it affords (classified by the Army in one of three categories). This can be accomplished in general terms over an entire sector, but for increased reliability we really needed a method of describing mobility cell-by-cell throughout the terrain, which led to the slope evaluation method described below.

This 'backwards' discussion of research and programming requirements is intended to provide the reader with the intellectual roadmap used in developing the thesis. Additionally, this section should provide context for the clearly limited scope of implemented software products and their relevance in the overall effort to produce truly intelligent software agents.

B.   ASSESSING DIGITAL ELEVATION DATA

I used the a class file from the OpenMap™ 4.5.4 open source software package to read publicly available Digital Terrain Elevation Data (DTED) Level II, with elevation posts 30 meters apart.   This provided an enormous amount of detail that proved initially quite overwhelming for a program designed to operate at a higher level. Experimentation with lower detail levels (obtained by simply averaging posts in either 2-by-2 or 3-by-3 groupings) produced satisfactory performance for general descriptions of terrain and mobility corridors, but an unsatisfactory amount of detailed information which would be required at the individual vehicle level during our highest level of resolution.   At this

point in the research, I had been using the idea of mobility corridors for classifying terrain. I classified mobility corridors by conducting a post-by-post traversal of the entire data set. At each post the algorithm considered all adjoining posts with minimal changes in slope and if small enough, added that post to the same mobility group. This process continued for each new post added to the mobility group until all possible adjacent posts had been added to the mobility group. At this point, we returned to the next data point in the set which had not been added to a mobility group and continued the process. After classifying every data point as a member of a mobility group, I then compared groups using Manhattan Distance (maximum length and maximum width) and by number of points contained.

For the National Training Center data set, either of these comparisons yielded one very large mobility region encompassing most of the low ground and thousands of individual mobility regions in the rocky mountainous regions. This was not as useful as anticipated, and had the secondary disadvantage of not considering subtleties in terrain – either the slope was gentle enough to allow the point to be added to that particular mobility region or it wasn't. The net effect of this approach was that one could adjust the slope index to either make all slow-go terrain sections become their own separate mobility regions (which has the effect of turning Slow Go terrain into No Go terrain as those points are excluded from the Go mobility regions) or to make all Slow Go regions become part of the Go region (thereby masking Slow Go terrain and incorrectly categorizing it as high speed Go terrain).

This experience above, and the weaknesses of a binary mobility evaluation, led to a reclassification of terrain data post by data post for use by the gas exchange assessment program. This process applies a similar slope evaluation methodology when traversing the database but compares slope change for each data element, or terrain posting. Specific slope indices vary by type of vegetation, vehicle, soil composition, and numerous other factors not particularly relevant to this thesis. As such, the indices were adjusted until they matched the author's personal opinion for a mechanized moving force. Go terrain data cells were classified as cells where the maximum slope was less than 5% per 30 meter post, Slow Go terrain was between 5% and 8%, and No Go terrain where the slope exceeded 8% from one post to another 30 meters away. No particular

significance should be attached to these slope indices, as the results of gas diffusion are based on the maximum allowable traffic speed assigned to each cell. For purposes of this thesis, I assigned a maximum speed of 25 kilometers per hour (kph) to the Go terrain cells, 10 kph to the Slow Go cells, and less than 1 kph to the No Go cells. One of the strengths of a gas-based terrain analysis is that one can very simply assign several layers of trafficability information to a cell by simply adjusting the gas diffusion properties of that cell. Gas diffusion as a model of evaluating terrain is discussed further in following sections, but this approach of classifying a database using multiple levels appears to be quite beneficial and extensible to multiple use cases.
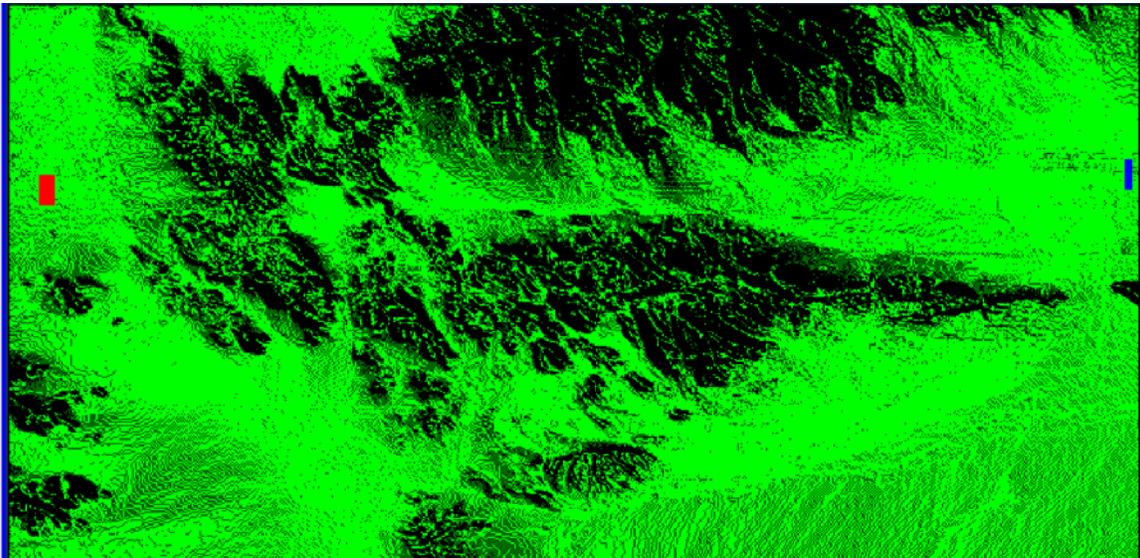
Figure 1.   Terrain Map showing Go, Slow Go, and No Go areas.

For this thesis, we classified each post for its capacity to pass tracked vehicles (or maximum speed), but one could easily extend the analogy to a nearly unlimited number of cases across a wide spectrum of modeling applications. Any application which is interested in solutions involving most efficient or most likely traversal of a complex environment composed of multiple individual elements would seem to be good potential matches for a fluid-based system such as the gas diffusion model described above. At its essence, this model produces a field of gradient vectors from which we're able to predict the movement of seeded particles at regular start points around the source. One can envision that similar treatment of many different problem sets would yield similarly believable results. Foremost among the models many strengths are its ability to represent

the individual gradients for every single cell in an efficient manner to produce global effects. It is this ability to model a wide variety of individual gradient values which causes the model to be such an attractive candidate for so many other applications. This approach is particularly well suited for systems operating with variable measures of success or 'goodness' - - fuzzy logic systems, cognitive evaluation systems (such as amount of trust in an individual as part of a belief network), fluctuating electronic systems (bandwidth, heat, or capacity of a physical network), and of course physical earth systems such as the oil porosity of a terrain sample could all be modeled using similar gas diffusion models and derive realistic traversal patterns for the transfer element in question (truth, trust or information, electronic data, and oil from the examples above).

B. FLUID FLOW MODELING FOR TERRAIN

As mentioned earlier, the decision to use gas diffusion as a method of modeling human behavior was based on recurring use of fluid-based terms by military authors and subject matter experts as they describe the movement of forces across the terrain. Example terms include phrases such as "natural lines of drift," "flowed through the gap," "poured across the desert," and "path of least resistance." I had a digital terrain model but no elegant solution to evaluate likely movement routes through the terrain and began searching for simple methods of modeling water moving through a dry streambed. This research led to Jos Stam's papers (discussed in Chapter II) on visually representing gaseous phenomena using diffusion from which I developed a similar approach of evaluating human movement through terrain using gas diffusion as my representative fluid flow system.

The mechanics of the gas diffusion model are quite simple. Each point in the data set is treated as a cell in the terrain model which begins with a gas concentration of 1, and with a maximum limit for passing gas to each of its neighbors. For simplicity, I treated each cell as a square, only able to exchange gas with each of its four shared-wall neighbors, thus the maximum exchange (out) for any given cell is 25% of its current volume.

The expected enemy approach direction (or an edge of the map zone) is treated as a source. Each source cell diffuses gas at the maximum rate with its neighbors and is re-

instated to full capacity (index value of 1, or 100% full) at the beginning of every turn. The source cells continue to "pump additional gas" into the system at every turn.

At the other "end" of the terrain set is the expected enemy objective area. This can be a single terrain post or a large geographic area. These cells are the sinks. Each sink is able to absorb gas at the maximum rate from its neighbors and immediately empties back to 0 at every turn.

For every turn, the model processes outgoing gas exchange for every cell with each of its neighbors based on the current concentration of gas in that cell times the maximum exchange rate of the cell. I used maximum exchange rates of 25% for the Go terrain cells, 10% for the Slow Go terrain cells, and 0% for the No Go terrain cells. The exchange rate is limited by the minimum exchange rate possible at the two cell edges. A Go cell only exchanges 10% of its volume along the edge that it shares with an adjacent Slow Go cell while it may also exchange 25% of volume on the edge shared with another Go cell.
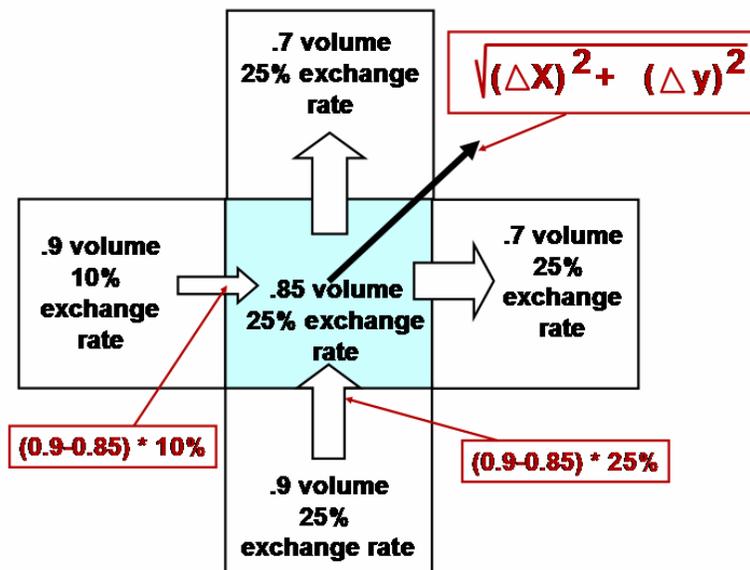
Figure 2.   Gas Diffusion Between Cells.

Outgoing gas changes are stored in a buffer until all outgoing calculations are complete, then the results, both outgoing and incoming gas amounts, are posted to each cell, the sources are regenerated to 1, the sinks are emptied to 0, and the process is

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repeated. As the process continues, gas concentration in the cells closest to the sink quickly approaches 0 and those cells serve to drain the cells around them. This process continues throughout the duration of the model until equilibrium. Evaluation prior to achieving equilibrium is visually interesting but practically irrelevant, as the model must be at (or close to) equilibrium to tell us where the fluid (or gas, in this case) will truly flow. The true benefit for evaluating movement occurs when the gas reaches a steady state approaching equilibrium. As the gas exchanged for each cycle reduces to the point of minutely small changes for the entire database the field of gradient vectors becomes useful for analysis. Though not true equilibrium, as the amount of gas exchanged approaches zero we have a state of nearly unchanging gradient vectors upon which to base our route estimation.

Though a near equilibrium state could be easily measured mathematically by comparing percentage of change from one cycle to the next, I implemented two visual screens to track this process more intuitively. The first of these is a concentration of gas for each cell reflected as a percentage of blue. Each cell is painted in standard Red-Green-Blue color pattern with a value of (0, 0, 255-254*percent of gas). Some cells cannot exchange gas because they are surrounded by No Go terrain. We paint those cells where the percentage of concentration is greater than 99.99% (or, where there has been no transfer out of any gas) with their normal color. As such, it's interesting to note the places where the gas cannot diffuse (and where it is thus very unlikely for any force to be). When the terrain grid has reached equilibrium the amount of blue should be equally spread from near 0 at the sink (very bright blue) to near 255 (very dark blue) near the source. It's important to note that even remote areas will eventually reach the same concentration of gas as their counterparts on the higher-speed diffusion sections in other parts of the database. This is a reflection of a gas's property of expanding to equally fill the volume of any container. Two points which are equidistant between source and sink will both have gas concentrations of approximately 50%, regardless of whether one point is in the middle of a high speed open portion of Go terrain or the other is in a remote section of extended Slow Go terrain.
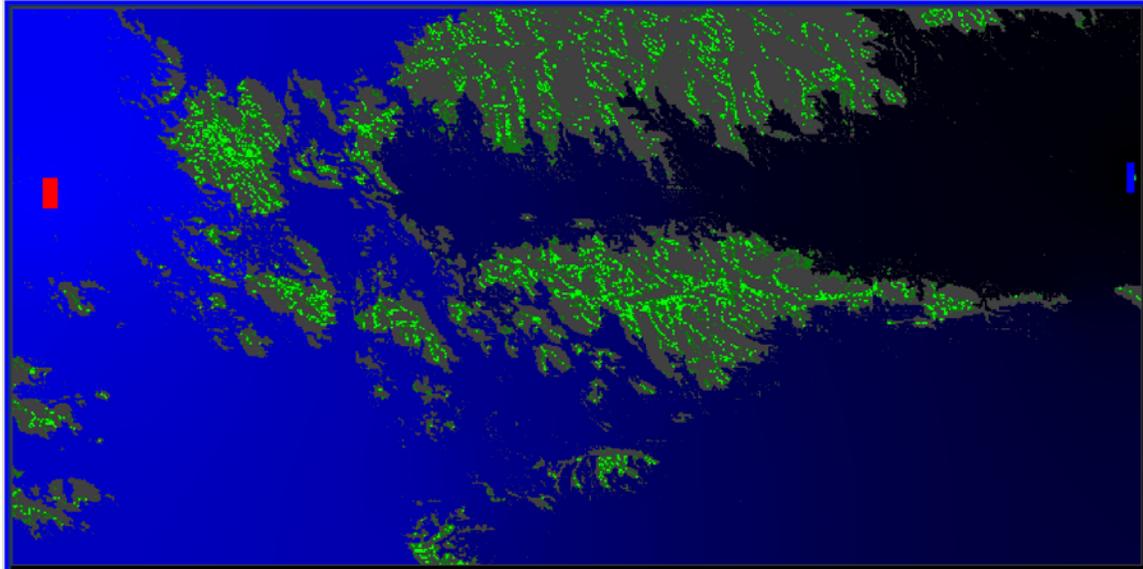
Figure 3.   Gas Concentration Levels.

Note in Figure 3, above, that the diffusion process is nearly complete for this model in the southern sector as it varies uniformly from light to dark. In the center, however, the diffusion process is still ongoing which we can tell by the darker center section's extension further to the left than the lower section of passable terrain.

The second visual cue is similarly deduced, but rather than relying strictly upon gas concentration instead it displays gradient magnitude as a fraction of red. As shown earlier in Figure 1, each cell in the database exchanges gas with its four shared-wall neighbors, or along the x and y axes. We capture the total changes in x and total changes in y for each cell and treat these changes as the components of a force vector at each cell. See below for a figure describing this process from our earlier example.
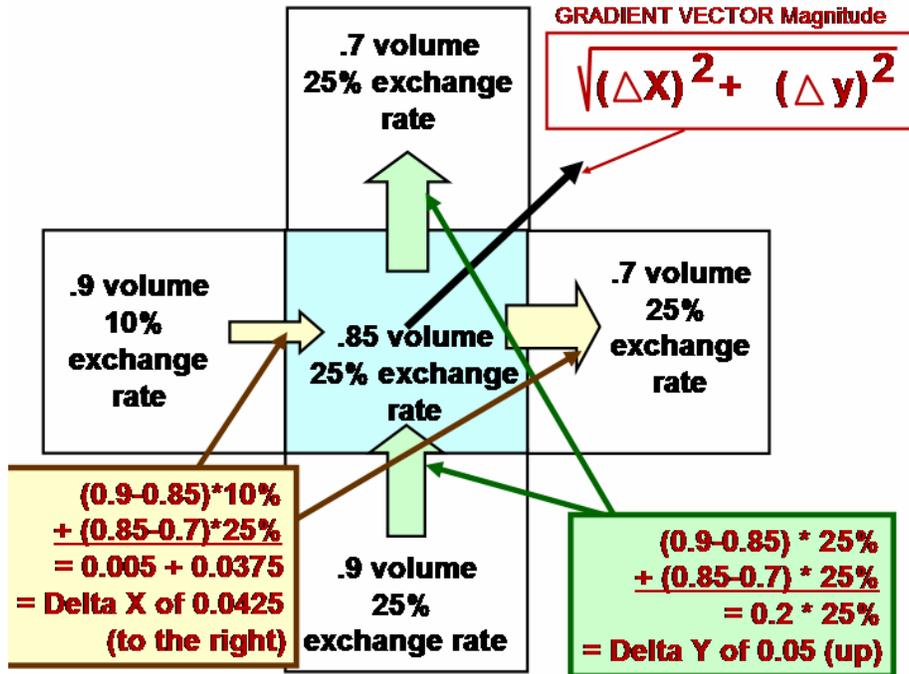
Figure 4.   Delta X and Delta Y.

The gradient vectors below which indicate both the direction of the vector from the center of each cell, but also the magnitude. Gas flowing through the convoluted area on the top of the picture moves much more slowly than that to the bottom of the picture as can be seen by the size of the gradient arrows. This is both intuitive and informative.
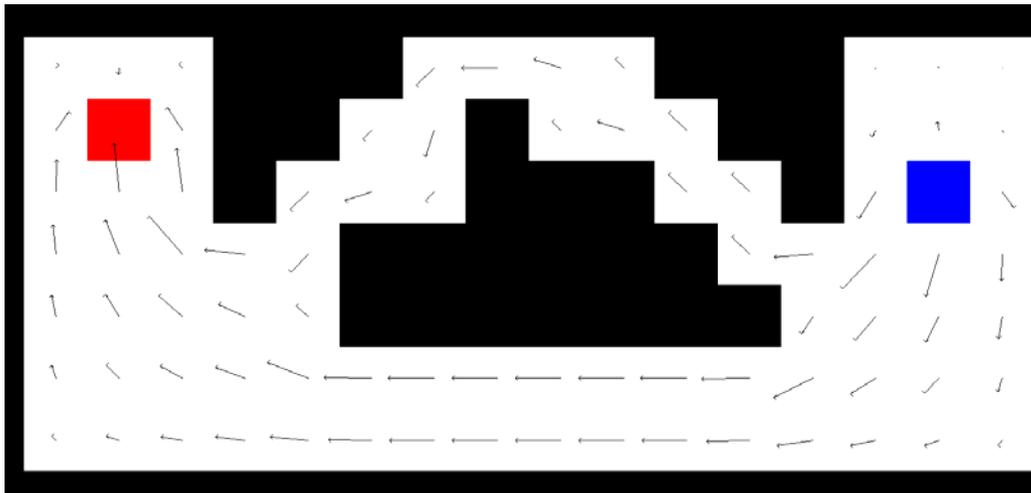
Figure 5.   Gradient Vectors.

The gradient vectors for each cell form a vector field which will become quite useful in our analysis of routes as I will discuss in the next section. However, we can also use this information as a means of evaluating the degree to which the model has

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reached equilibrium by producing a gradient magnitude page. Shown below, the gradient magnitude view is a redraw of our terrain field where each cell's gradient magnitude (as a percentage of the highest magnitude vector in the field) determines the brightness of the red color. A terrain field at or near equilibrium will have high magnitude gradient vectors at both the source and sink as well as at each chokepoint or narrowed area along the high speed movement corridors between source and sink. Similar to the Gas Concentration figure, for gradient magnitude I left the areas with magnitude of less than .01% colored in their original pattern to indicate that the lack of movement gas diffusion in those cells. This view has a secondary advantage of also providing a very intuitive picture to the user of the gas flow over time. It's quite clear by the bright areas on this frame which pieces of the terrain experience the highest gas transfer rates, and where the areas of concentrated high vectors exist. This information can be then used to pinpoint areas of risk to a moving force as they become more physically concentrated, key terrain (as it overlooks these places where the moving force assumes higher risk), and potential anchor points for a defensive deployment. These benefits will be discussed later.
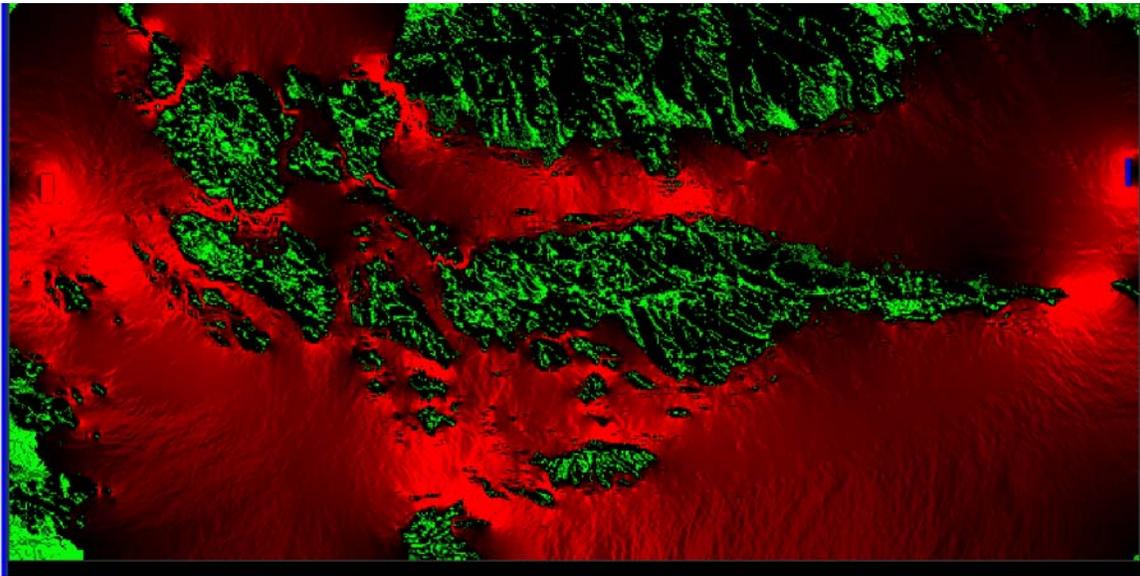
Figure 6.   Gradient Magnitude Levels.

C.   PRODUCING AVENUES OF APPROACH

The process of producing avenues of approach from this point (given a gradient field produced as described in the previous section) is similarly simple to implement but

produces an excellent representation of avenues of approach through a terrain sector. Borrowing from the fluid-like movement properties of a multi-vehicle military unit, avenues of approach are calculated by means very similar to following floating particles down a stream. Beginning at the source, routes are generated at each possible adjacent cell. By design, this limits routes to a fixed number for ease of computation and viewing. If desired the number of routes is easily adjusted by increasing or decreasing the size of the source. Note above that in the figures above and to follow the source size is 5-by-20 cells, so the program will generate a maximum of 54 routes, 50 along the four walls and one in each corner. Beginning at each of these cells, the program interpolates a new particle position for each turn based on the influence on the particle by each of the closest gradient vectors. This process is displayed in the figure below.
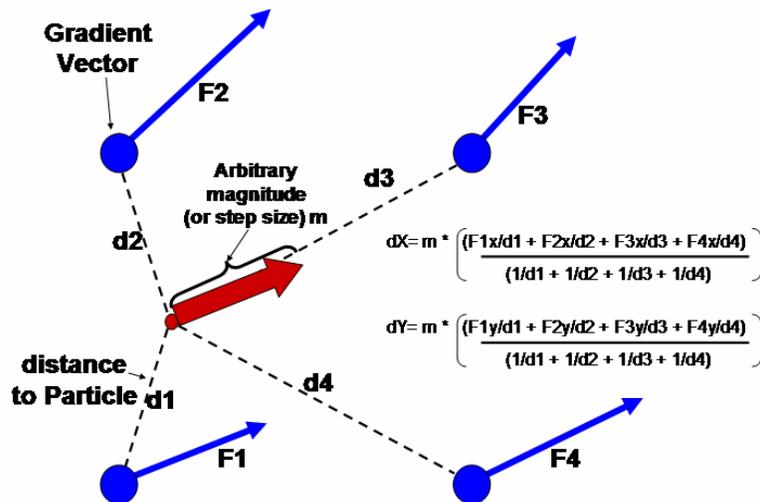
Figure 7.   Particle Flow Interpolation.

This process is repeated until each particle has reached the closest sink. Interpolation is a necessary step in order to represent a realistic movement through the gradient field. Initial research without interpolation produced routes which hopped from vector to vector without considering the forces which would act on the particle as soon as it left the specific vector point. In the diagram above step size is listed as an arbitrary magnitude m. For this program I commonly used a magnitude of 0.4 (or 40% of the distance between posts) as this forced at least two interim checks between each set of influencing vectors. The route selector is not programmed to only consider the closest

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four vectors, but to consider all vector posts within a distance of 1.5 cells from the particle. This ensures that each particle always received input from a minimum of four vectors as well as considering both past and future vectors when transitioning between one block of four vectors to the next.

One interesting result of this approach is the effect of edges upon movement of particles. Rather than force particle movement to never intrude upon the No Go terrain cells, instead the program treats a No Go cell as one with a zero magnitude gradient vector. As a result, then, we experience limited edge effects when particles travel adjacent to No Go terrain as their forward movement (to the sink) is slowed with only half as many gradient vectors to propel them forward. These edge effects also produce occasional visual anomalies for small terrain grids as the routes (especially the slower routes to the sink) appear to travel within the bounds of the first No Go cell adjacent to a Go or Slow Go terrain cell. Its worth noting that this is a purely visual anomaly produced by our representation of point values (the gradient vectors for each data point) as if they were uniformly distributed across an entire grid cell. In fact, the changes between data points are continuous in real life, and allowing routes to drift into the first cell of No Go terrain grid is akin to the physical nature of waves lapping against a rock before returning to the greater stream. An example of this anomaly is shown below.
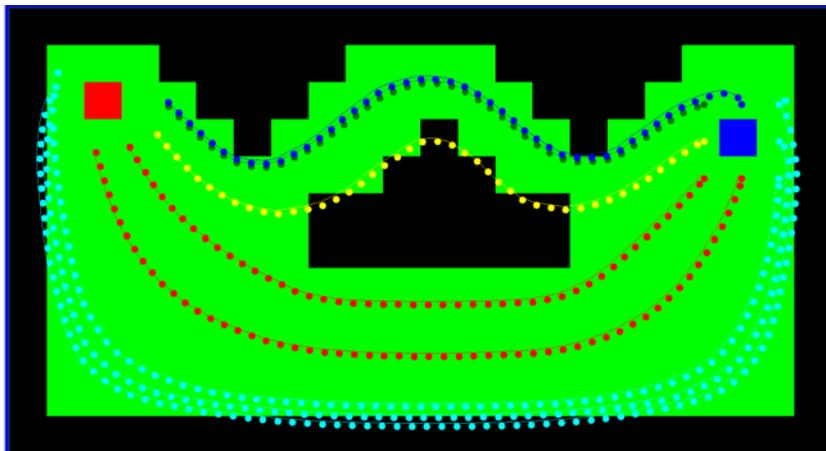
Figure 8.   Edge Effects.

Obviously a physical model of fluid movement through a complex grid would be incomplete without a formal, mathematical treatment of edge effects, turbulence, coefficients of drag, and fluid density. For our purposes, however, the net effect of

interpolating particle movement with zero magnitude edge vectors results in slowed particle movement along exposed No Go terrain. Both the decision to forego a full mathematical treatment of fluid movement, and our acceptance of de facto edge effects in this simple model appear to be reasonable and realistic given our design parameters.

Avenues of approach through our terrain are evaluated based on speed of particle movement through the grid in total time from source to sink. For ease of visual interpretation, all routes depicted in this program are displayed by color ranking based on relative time to complete the movement. The fastest twenty percent of routes are colored in red, followed by yellow, green, blue, and cyan. Shown below are the avenues of approach generated for a portion of the terrain database discussed above.
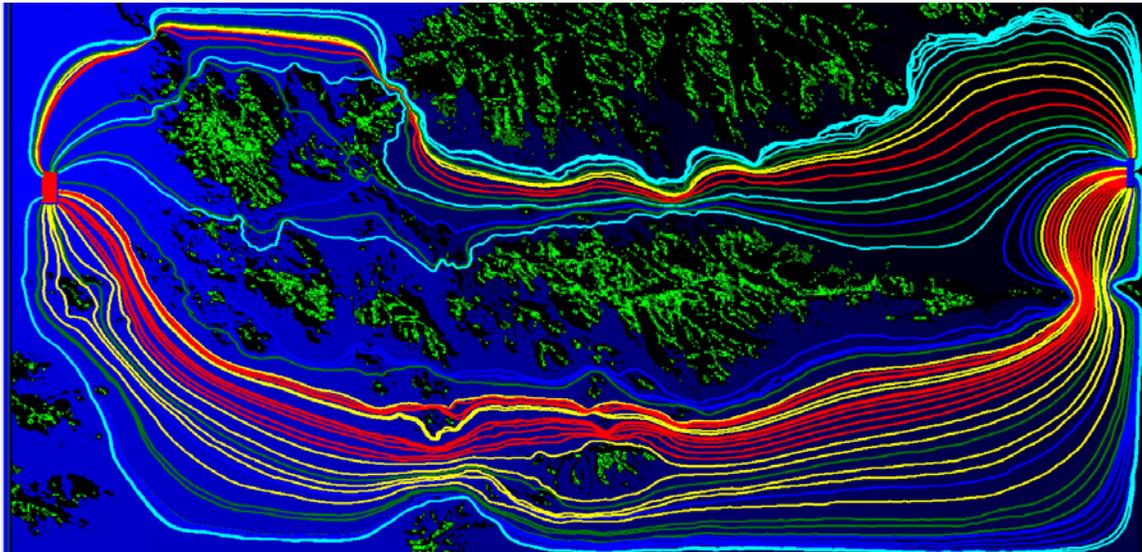
Figure 9.   Avenues of Approach (Gas Concentration Background).
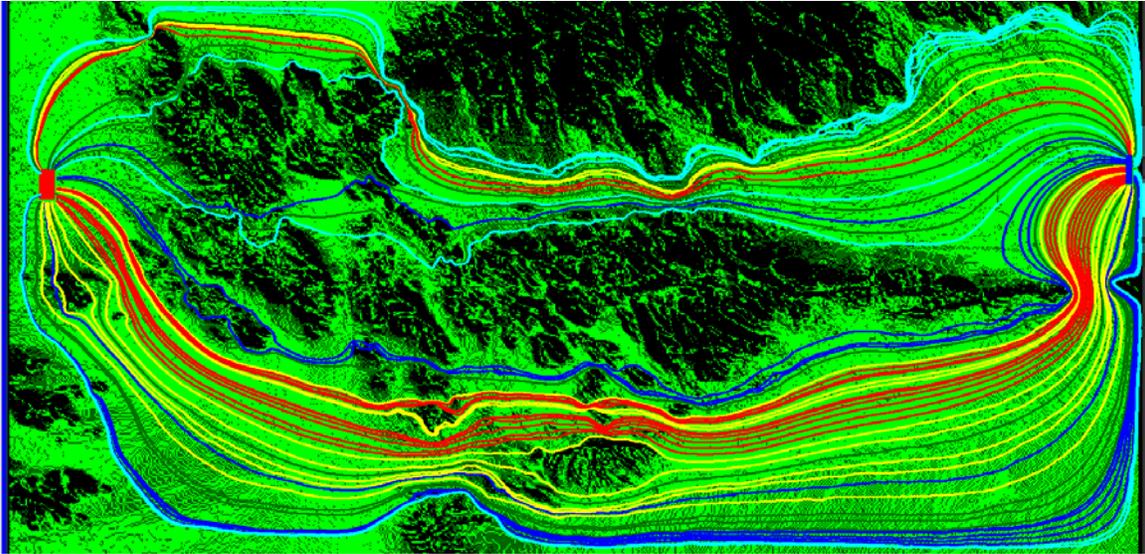
Figure 10.   Avenues of Approach (Go / Slow Go / No Go Background).

Note that this approach describes most likely avenues of approach from a certain point and is used as a means of generating favorable terrain indices for use by a defensive positioning algorithm. As such, the routes are only calculated one time from an estimated source location. Each route from this analysis receives a score relative to its likelihood of use.   The defensive deployment algorithm uses these values in one of the deployment goals for its agent based implementation. Agents seek positions where they can cover a maximum amount of likely avenue of approach posts with direct fire. Considering the alternative implementation of this software, using it to provide a continuous assessment of an attacking enemy force (rather than considering routes as a means of predicting the location of a defending enemy force), our initial result would be identical, but at each chokepoint or decision point we'd want to reestablish a new gradient field based on the decision point as source and predict further routes into zone from that point.   This recursive application of terrain analysis is applied throughout the battle by Intelligence officers and would need to be mirrored by this software in order to replace some of these functions in software.

D.   GENERATING DEFENSIVE ANCHOR POINTS

Each of the defensive patterns applied in this thesis assumes use of an anchor point around which the defense is arrayed. The anchor point is the key terrain which provides the defending force with a significant tactical advantage. The critical terrain is

that which, by its very nature, requires an attacking force to slow its advance, change direction, compress to smaller width, change formation, or otherwise modify his planned attack so as to sacrifice some degree of tactical advantage. Describing this terrain to a computer program is challenging, as its definition includes elements of both the art and the science of warfare. Described below are two approaches for selecting anchor points. Both of these approaches rely upon a scientific rather than artistic appreciation of combat tendencies, but both appear to produce a reasonable selection of anchor points for our use.

1.   Minimum Perpendicular Distance Search

Using this technique, the program considers the total consecutive Go terrain points which are roughly perpendicular to the preferred (or most likely) avenues of approach. The best defensive anchor point is that portion of the route with the minimum distance of Go terrain. Beginning at the source, the algorithm traverses the most likely avenue(s) of attack towards the objective. At regular intervals along the route, we conduct a search to determine the minimum possible gaps generally perpendicular to our direction of travel. Generally perpendicular can be assumed to mean that we seek outward from the avenue of approach with a goal of reaching the exterior borders of our sector or zone. Within that constraint, however, it is permissible to search within a broad range of search directions so long as the ultimate objective of reaching the flank borders is kept foremost in mind. Rather than keep track of specific angles from point of origin we allow these flank goals to force generally perpendicular lines using an A* search. For sake of computing efficiency, we can reduce the scope of this search to only those points where the directly perpendicular line (a north-south line for the scenario on this thesis) contains a minimum number of No Go terrain cells such as fifty percent. Once over the fifty percent threshold, the program then conducts an A* search in each direction, with cost computed as the inverse of trafficability. Cost is a factor of 1 x distance in Go terrain plus 0.4 x distance in Slow Go terrain plus 0.01 x distance in No Go terrain. The A* estimate function would then be simply the straight line distance to the border assuming minimal cost plus cost traversed to date. The combined A* minimum cost for each direction becomes the chokepoint distance for that particular point along the route. The point with the minimum chokepoint distance along the enemy direction of attack is

our first potential anchor point. Subsequent points on either side of optimal are candidates for forward, subsequent, and alternate defensive positions.

2. Maximum Gradient Value Search

An alternative method of selecting potential chokepoints is to take advantage of the gradient magnitude values used to construct the intuitive picture in Figure 5, Gradient Magnitude Levels. Areas of highest gradient magnitude from the fluid model represent the concentration of most likely avenues of approach through restrictive terrain. Limiting our search to only those cells with the highest 20% of gradient magnitudes appears to produce a good representation of chokepoints for the NTC data set. Each contiguous cell with gradient magnitudes over 80% of maximum is added to a list of cells for that given chokepoint. Similar to the method described in the perpendicular search above, we develop an algorithm to ensure that our chokepoints are selected in sets which cover the entire breadth of the defensive sector. A similar A* search pattern will produce this result if we begin our searches at regular intervals along one boundary of the terrain set and search for the least costly route to the other boundary. Just as NoGo terrain cells cost 0.01 in the perpendicular search above, now high gradient cells also cost 0.01 to traverse. This should very quickly generate a list of points which contains all NoGo plus ChokePoint terrain cells that cover the width of the sector. Given the potential for multiple sets of acceptable defensive positions, we would not limit this search to the optimal combination of chokepoints and No Go terrain but would conduct the search throughout the depth of defensive sector to produce a number of reasonable alternatives for further consideration. Shown below are the top 20% of gradient magnitudes for this particular terrain set.
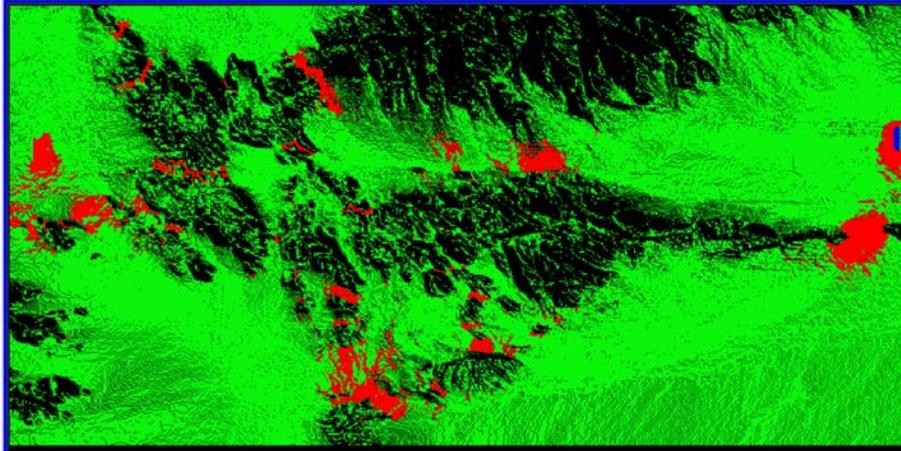
Figure 11.　Chokepoints.

The search algorithm described above has not been implemented in software at the time of this writing, but the general results from this search can be envisioned to look generally as depicted below by the blue lines, each line representing a set of points containing a combination of chokepoints and No Go terrain which would provide anchor points (center mass of each chokepoint concentration) for a reasonable defense of this terrain sector.
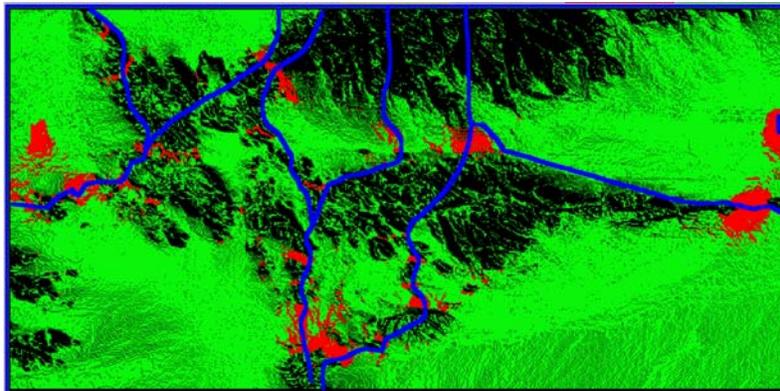
Figure 12.　Chokepoint Combinations for Defense of Sector.

One comment on this approach is that using an A* search to produce these combinations, while both optimal and complete, is also much more computationally demanding than the task may merit. Treating each section of contiguous No Go or Choke Point terrain as a separate entity would greatly coarsen the terrain set and reduce computation time exponentially. Several possibilities for coarsening the terrain are worth considering here, perhaps most promising would be use of a computational geometry approach for building convex hulls out of the edges of No Go and Choke Point terrain

sets to produce large polygonal structures from each contiguous set of terrain. While this tool is not implemented in this thesis' software, in concept this reduced grid would look similar to the figure shown below (assuming that each of the blue areas are single regions generated by the computational geometry method).
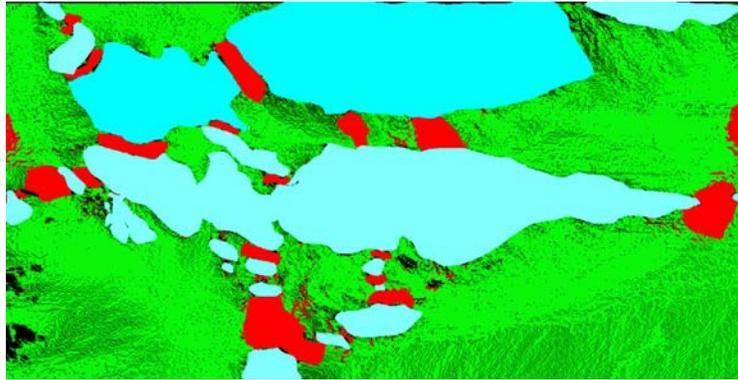
Figure 13.   Simulated View of Coarsened Terrain Grid.

3.   Considering Engagement Areas

Regardless of the approach selected for considering potential chokepoints, ideal defensive anchor point selection can be further refined by comparing chokepoints with terrain to their front.   A minimum amount of open terrain preceding the chokepoint is required before the chokepoint can be classified as truly good defensive terrain. Although the A* search described above will produce the most restrictive portions of potential enemy movement routes through a given sector, it does not consider the open terrain in front of the chokepoint which would be required for a defensive position. Similarly, the maximum gradient search will yield chokepoints of highest concentration of routes but not necessarily describe the potential defensive benefit of that chokepoint. Though not implemented in this thesis, there are two simple methods of comparing defensible terrain which would further refine the list of potential anchor points.

The first method would be a purely mathematical count of cells on the enemy side of the chokepoint within a certain distance (I'd use about 150% of direct fire range for the main weapons system) which are also contained in the list of likely routes identified by the fluid simulation.   Each chokepoint on our list would then have two scores; a minimum distance score, and a maximum engagement area score.   Further testing is required, but it seems that the sum of these scores' ranks (i.e.…the 2nd best chokepoint

distance plus best engagement area would receive a score of 3, etc..) would produce a very good anchor point candidate.

The second method of comparing defensible terrain would be to simply array the defensive template onto the terrain (as described below) and use the total score for the defensive deployment to compare anchor points. This method would consider the defensive engagement area size indirectly, as the agents receive higher scores for maximum coverage of engagement area cells, dispersion, and massed fires. It is the author's opinion that this method would give the better overall comparison of potential anchor points as it considers all of the relevant defensive positioning factors. One could almost consider this comparison as similar to Klein's mental simulation model whereby humans project the results of their decisions into the future to confirm or deny choices. Though more demanding (in terms of CPU cycles) than the first method, this way of refining chokepoints does seem superior for its breadth of scope.

E.   ARRAYING FORCES

Having identified a list of potential anchor points, or more accurately, the chokepoint or other key terrain around which to assume the defensive organization is arrayed, the next problem is deploying units of varying echelons onto the terrain in a coherent fashion. Although it is certainly possible to take a purely mechanical interpretation of defensive deployment templates and lay them down onto the terrain without considering defensive planning factors, I believe that a more robust solution is called for. Implemented early in my thesis research and described in concept here, is a program of semi-autonomous agents which adjust their positions relative to each other and to the potential engagement areas in order to achieve a maximum level of satisfaction, both as individual agents (representing at the platoon level), but also as groupings of agents representing companies, and battalions.

1.   Goal-Seeking Agents

The program assumes a basic knowledge of anticipated forces in sector, namely the expected unit type and size. While its conceivable that this program could be modified to consider minimum and maximum size force for a particular terrain sector, the current structure requires some knowledge of enemy; the type of unit to be templated on the terrain, down to vehicle composition and relationships. This information is readily

available from public sources for a variety of military organizations. For my initial software implementation I used a modified Motorized Rifle Regiment task organization, but the concept described herein work equally well with other size and type organizations.

Given a task organization, each platoon (or separate two-to-three vehicle element of that task organization) is instantiated as a semi-autonomous agent seeking to satisfy a number of goals. Borrowed from the Principles of War, the key positioning factors for each agent are Objective, Mass, Security, and Dispersion. The agents are deployed onto the terrain following a military standard deployment pattern. This pattern is also known as a doctrinal template, for it doesn't consider terrain, only enemy doctrinal distances and likeliness of adjacent positioning. Given the initial positions on the terrain (with the center of mass, rear of the template astride the anchor point selected in the previous section), the agents adjust to find the best terrain to maximize their particular defensive goals (or positioning factors). For a defensive position, these goals are translated as follows:

a. Objective

How well can the platoon meet its objective of destroying enemy vehicles? This is the primary mission of the platoon, to destroy enemy vehicles in the Engagement Area (EA). As alluded to earlier in this work, we do not specifically create an EA for each platoon or other element in the task organization. Rather, we classify the terrain throughout the sector with a favorable score if that terrain is likely to be traversed by a moving force. This is the reason for the fluid simulation, to create a value for each terrain cell indicating the likelihood of enemy movement on that particular piece of terrain. Only those cells indicated as potential routes will have EA values. All others will be rated as zero. Note that we don't require every cell to the sides of our generated routes to be filled. If there are enough routes created, the distance between them is so small that the program can obtain sufficient EA Score data by just adding the specific cells contained in each route. A platoon's EA Score is simply the sum of EA Scores from each of the route cells considered which are between one third and one hundred percent of the platoons' maximum effective range for primary weapons system. This range is an attribute of each platoon agent and compensates for differences in type of platoon without

requiring different algorithms. Limiting the search to the final two thirds of maximum effective range prevents the platoons from positioning themselves astride an avenue of approach to get the highest score, but rather encourages them to push just outside the avenue of approach in order to cover it with maximum fire but given some standoff distance as well. In addition to range limitations, EA score is limited to the points which are within plus or minus of 60 degrees from current orientation. Considering orientation allows the program to compare massed fires with adjacent platoons as well as having a secondary effect of organizing platoons around the exterior of an engagement area (facing in) rather than in the center of an engagement area facing out.

b. Mass

How well can the platoon mass fires with other platoons to achieve combined effects into the objective area? Here the program considers the number of adjacent platoons which are within the doctrinal deployment dispersion of a company and positioned on one of the platoon's flanks. A Mass score of 2 is added for every platoon within 60-110 degrees of the current platoon's orientation, a score of 1 for every platoon between 40-60 or 110-140 degrees of the current platoon's orientation, and a score of 0 for any platoon which is directly behind (0-40 degrees) or in front (140-180 degrees) of the current platoon. In order to prevent this factor from dominating, the Mass score is capped at a maximum score with 4 platoons in position to provide supporting (or massed) fires into the platoon engagement area.

c. Security

How well is the platoon secured? This is a difficult consideration to quantify, but for purposes of this program I assumed that security is a function of operating within the normal limits of the next higher echelon. A platoon within the doctrinal dispersion pattern of a company is adjudged to have a higher level of security than one which is exposed due to being too far away from the remainder of his higher unit.

Other lower-level security factors, while vitally important in real life, are not generally modeled well in constructive simulations and as such are not considered here. We recognize, for example, that a platoon's security depends a great deal upon a plan for continuous observation, noise and light discipline, flank protection,

supplementary and alternate positions, and properly emplaced fighting positions for good observation and protection against direct and indirect fire. None of these effects are specifically modeled in most constructive simulations, so for simplicity's sake we define security as the platoon's deployment within the normal tactical bounds of his next higher headquarters, the company.

For a platoon, the security is based on the distance from the platoon center of mass to the center of mass of its higher headquarters. If that distance is 55% or less than doctrinal deployment distance of the next higher headquarters, then this score is a 1. If between 55% and 75% of doctrinal distance, then the score is a 0.8, if less than 100% of range the score is 0.6, if less than 120% of distance the score is 0.2, and greater than 120% the score is zero. This abrupt drop in scoring highly encourages each platoon to deploy itself within the confines of its' higher headquarters normal deployment range. For my initial implementation I repeated this score two times, once each at company and battalion levels.

This approach is extensible up to at least regimental level, but the logic grows progressively weaker at higher echelons. Not only are higher echelon military units more likely to be assigned disparate missions far removed from the next higher headquarters, they are also much better able to defend themselves without requirement for adjacent unit or higher headquarters support. An exposed regiment is much more secure than an exposed platoon as the regiment can be assumed to control a much greater amount of internal protection, fire support, and maneuverability to secure itself without external support. As such, this factor is probably only relevant at regimental level and below. Positioning within a Division or Corps would require a different set of positioning logic and indices; our simple security algorithm doesn't extend to that level of force complexity.

d. Dispersion

How well has the platoon achieved dispersion from its' sister units? Protection from massed artillery and other fires depends upon maximum dispersion in order to avoid creating a lucrative target. For this factor the program simply adds up the number of sister elements within 150% of the normal platoon level deployment footprint. If there are no platoons within this distance, dispersion factor is 1. If 1 platoon is this

close, dispersion factor is 0.7, and if 2 platoons the factor drops to 0.2. Given the tremendous danger of massing friendly forces, the dispersion factor continues to degrade for massed platoons greater than 2, with a score of -0.7 for 3 platoons and an additional decrement of -0.5 for each additional element.

e. Overall Goodness

Each of these factors above is considered in an Overall Goodness score for the platoon's potential position. These overall goodness scores are computed for positions at each of the eight cardinal directions of movement at two different ranges, one at 50% of platoon defensive position size, and the other at 100% of size. At each of these 16 positions, the program further considers orientation when determining the EA score. In order to avoid major orientation changes in any one turn, we limit the orientation sweep for a given turn to plus or minus 120 degrees (in 30 degree increments) from current angle of orientation. The highest total goodness score for a platoon of these 144 options (16 positions and 9 potential orientations per position) is selected and that platoon moves to that position immediately.

Moving platoons immediately (rather than storing future locations in a change buffer and moving all units at the beginning of the next turn) does force a ripple onto the entire deployed force based on the first platoon moved, but it also allows each successive platoon to consider a better version of truth than would be possible if no unit moved until the beginning of each cycle. In order to prevent the left-most platoon from exerting undue influence upon the self-correcting moves of the entire unit we can select the "first" platoon to move randomly at each cycle.

The Overall Goodness factor for this approach is the "slope" which each agent is attempting to climb in our Highest Gradient Hill Climbing (HGHC) architecture. While this is certain to produce locally optimized solutions, there is no guarantee that these deployment results are globally optimal or that our scoring factors in the Overall Goodness formula are appropriate. I will discuss adjusting the scoring factors for the Overall Goodness formula in the Validation chapter, but will expand upon local vs. globally optimal solutions here.

The concept of a globally optimal solution implies that the factors involved are sufficiently mathematically accurate as to produce a truly optimal solution. In the opinion of the author, this is simply not the case when defining military deployments. The goal of this program is to represent a credible version of computer-generated, human-like results. We use a local optimization with agent based programming to produce the most credible deployment template for this terrain set given this starting position, and given our current limits on position adjustments. Globally preferred solutions are obtained not by allowing our agents to peruse the entire database. Rather, we use directed heuristics to focus our search and determine the best deployment locations for each anchor point. Next, we compare the summed satisfaction scores, or Overall Goodness ratings, for each anchor point. The anchor point with the highest Overall Goodness rating becomes our most likely defensive deployment location and the program deploys forces based on the results of the Highest-Gradient, Hill-Climbing (HGHC) semi-autonomous agent procedure described above. This represents our best estimate of the situation until we receive incoming reports of actual vehicles and equipment, at which time we apply slightly different techniques to react to updated information.

F.   REACTING TO UPDATES

All previous discussions in this thesis have been implemented in software. What follows is a conceptual treatment of using computer vision techniques to recognize deployments of individual vehicles as members of a platoon, followed by a coarsening of the grid to compare platoons as members of a company. By this process one can evaluate incoming or known data about specific vehicles and equipment and match this information with a known pattern. For purposes of this concept discussion, I will show very general deployment patterns. In practice, rather than use these general deployment patterns, the starting point for template comparison would be the deployed situational template described in the preceding paragraphs.

1. Platoon Detectors

Just as the human eye makes use of edge detectors by use of binary receptor cells tuned to recognize a particular pattern, so too will we describe a deployed platoon as one

of five different combinations of vehicles that, when satisfied, will elicit a recognition stream called Platoon.

For purposes of argument, we assume that a platoon is composed of five possible combinations: 3 tanks, 3 tanks and 1 BMP, 3 BMPs, or degraded platoons of either 2 tanks or 2 BMPs. Additionally, we assume that normal platoon dispersion is within a 400m area, and that this distance can vary by +/- 50%. We'll encode each reported tank with a value of 3 and each reported BMP with a numeric value of 1. For simplicity's sake, we'll assume that each platoon will thus be arrayed inside a single area with maximum dimensions of 600 meters wide (perpendicular to the orientation direction) and 400 meters deep (in direction of orientation). The final assumption is that within the platoon's boundaries will only be one platoon; no overlapped vehicles from other platoons. Given these parameters, our general platoon templates are as shown in the following table. Any score over 3 within a given 400x600m window in our database we'll classify as a platoon, using the higher scores to break ties when there are two possibilities. We won't allow any platoons to be defined with any amount other than combinations shown below, so all reported vehicles will be classified as either single vehicles or members of one or more platoons.

	Platoon Composition (BMPs/Tanks)				
Tanks	0	0	1	3	2
BMPs	3	2	3	0	0
Score	**4.5**	**3**	**7.5**	**9**	**6**

Table 2.   Platoon Composition Table.

Next traverse the database to identify and mark platoon locations. For each reported vehicle search the area within 600x400 meters of that vehicle to determine if there are other vehicles present. If there are additional vehicles present as we move the 600mx400m window in all directions around the first vehicle encountered, the highest score is identified as a platoon and those vehicles identified as members of a specific platoon so that we don't consider them on the subsequent traversals. This process is described in the figure below.
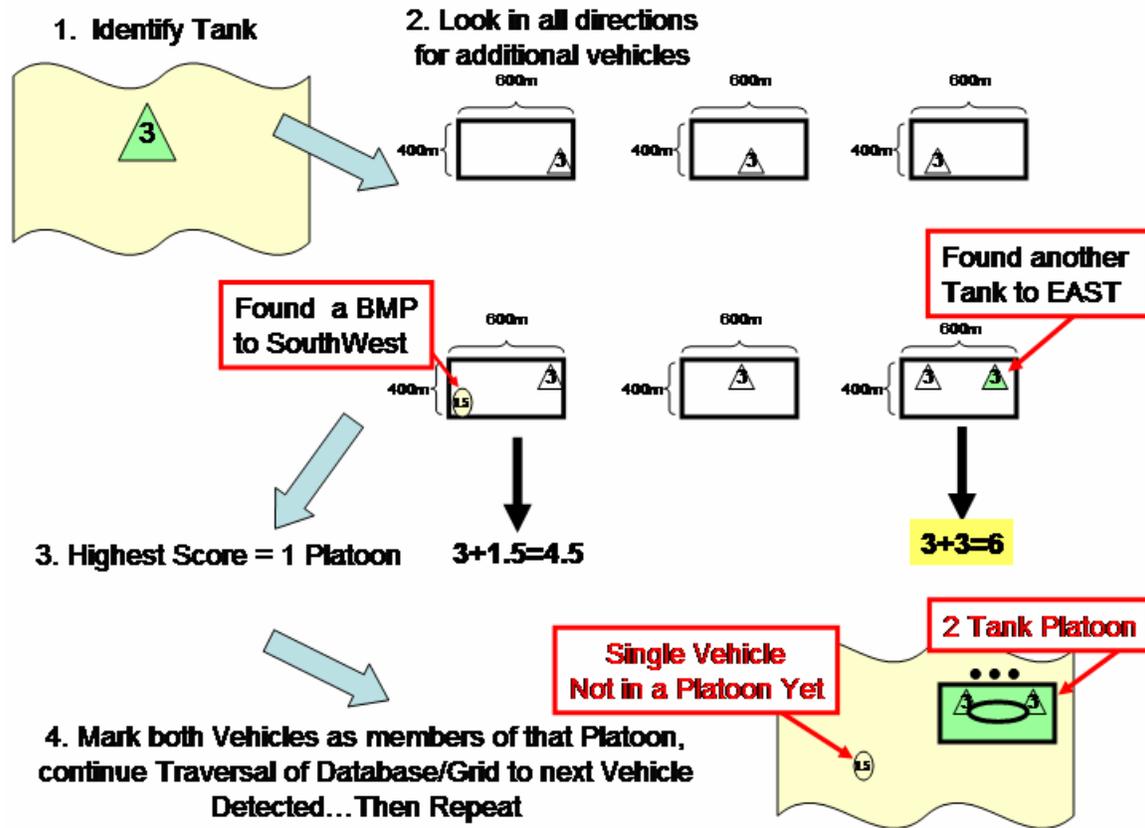
Figure 14.   Sorting Vehicles into Platoons.

At the end of this process will be a number of platoon-sized rectangles on the grid. Next we coarsen the grid so that it no longer displays individual vehicle positions, but a representation which allows for faster computing while preserving our ability to recognize imperfect alignment of our template with the reported vehicles. For purposes of this discussion I'll coarsen the grid to consider 200m squares only. Platoon locations are allowed to occupy 3x2 grid squares on our coarsened grid. Note that this coarsening is not simply conducted as a means of preserving CPU cycles, but is also useful in allowing us to repeat the template comparison process at successively higher echelons of organization and space with minimal effort.

2. Company Detectors and Pattern Matching

At the lowest level of computer vision, the program did not attempt to force vehicle deployments to match a specific pattern. While possible, it is the opinion of the author that platoon dispersion patterns, while varied, do not have sufficient tactical significance at this level to warrant specifically attempting to template their deployed

formation type. A platoon defense on line versus a platoon defense in a V are remarkably similar in nature and are not remarkably different in their ability to produce tactical results on a battlefield. As such, the platoon level search is the more general approach of a moving window around each detected vehicle until all potential platoons are classified as such.

For the company level, however, there are significant tactical differences to be found in both the company's ability to generate tactical effects as well as inference about future or potential intentions.   For example, a company defending on line (three platoons abreast in a generally linear manner) is able to place the maximum amount of massed direct fires at maximum range to considerable tactical advantage. The analyst can gather information about enemy intentions from this formation in that the company has exposed all of its combat units simultaneously with little apparent regard for flank protection or a reserve capability. These actions indicate that the company is deployed with either the intention of displacing to a subsequent position (hence the willingness to engage with all forces at one time) or that it has an assumed flank security and/or a reserve provided by an adjacent or higher unit. For these reasons, at company level and above, it's necessary to compare observed and known forces with a suite of potential deployment formations. It is not enough to simply extend the platoon methodology by a factor of three and lump the highest concentration of vehicles together as companies.   We need to know deployment and organization information, and thus will borrow from the properties of the human eye's edge detectors to create a series of graduated templates to compare with our known information.

For purposes of this conceptual discussion, I have created six simple company deployment templates, each of which is 12 grids in depth by 18 grids in width. Orientation of defense is assumed to be in the depth axis, and each grid square is 200 meters by 200 meters. Within each pattern, platoon locations are expected to occupy six grids – 3 wide by 2 deep. Each grid square in the pattern is weighted with a value between 0 and 3. By design, the center of each templated platoon location cannot cover more than 4 squares valued at 3. This is tacit recognition that there are no perfectly aligned units and we thus avoid artificial (and coincidental) perfect scores that could skew the results when compared to other, equally valid, deployment schemes.

We score the templates based on the previous definition of a platoon as 2-4 vehicles which occupy a 400m-by-600m space. Once a platoon has been identified, every space within that rectangle is counted as a "1" and is multiplied by the score from the closest fitting template. Given this, each platoon can "cover" all four of the center squares to achieve a score of 4x3=12 points plus the platoon will have two more squares covering template weights of 2. Thus, a "perfect" alignment of reported vehicles to a template for this discussion would receive a maximum of 4x3 + 2 x2 = 16 points per platoon x 3 platoons = 48 points. Sample company deployment templates are shown below.

Company - 2 up, 1 back																	
0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0
0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0
0	0	0	0	0	1	1	2	2	2	2	1	1	0	0	0	0	0
0	0	0	0	0	1	1	2	3	3	2	1	1	0	0	0	0	0
1	1	1	1	1	1	1	2	3	3	2	1	1	1	1	1	1	1
1	1	1	1	1	1	1	2	2	2	2	1	1	1	1	1	1	1
1	1	2	2	2	2	1	1	1	1	1	1	2	2	2	2	1	1
1	1	2	3	3	2	1	1	1	1	1	1	2	3	3	2	1	1
1	1	2	3	3	2	1	1	0	0	1	1	2	3	3	2	1	1
1	1	2	2	2	2	1	1	0	0	1	1	2	2	2	2	1	1
1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1
1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1

Figure 15.   Company Deployment Pattern – Two Up, One Back.

Company - Echelon Left																	
0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
0	0	0	0	0	1	1	1	1	1	1	1	2	2	2	2	1	1
0	0	0	0	0	1	1	1	1	1	1	1	2	3	3	2	1	1
1	1	1	1	1	1	1	2	2	2	2	1	2	3	3	2	1	1
1	1	1	1	1	1	1	2	3	3	2	1	2	2	2	2	1	1
1	1	2	2	2	2	1	2	3	3	2	1	1	1	1	1	1	1
1	1	2	3	3	2	1	2	2	2	2	1	1	1	1	1	1	1
1	1	2	3	3	2	1	1	1	1	1	1	1	0	0	0	0	0
1	1	2	2	2	2	1	1	1	1	1	1	1	0	0	0	0	0
1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0

Figure 16.   Company Deployment Pattern – Echelon Left.

Figure 17.   Company Deployment Pattern – Line Formation.

Similar to the platoon treatment earlier, we traverse our coarsened grid until encountering the first platoon location, and then search the grid in all directions for adjacent platoons. If there is more than one platoon within the maximum dispersion range of a templated company (..in this case the 12 x 18 grid box represents 3600m, or about 150% of normal tactical dispersion for a company), then compare the number values for these two to three platoons against their positions in the most likely templates. Each square inside a platoon box is represented as a 1, and all other squares in the grid are 0. Adjusting the company grids to achieve the highest possible scores for each template can be accomplished fairly quickly on the computer by applying the template at a number of different start points relative to the first platoon location, and we soon have a "most likely to be this formation" score generated by multiplying platoon grid by the company template indices.   An example application of this method is shown below for a three platoon pattern. Based on the highest score of 41, the best match (and most probable company deployment pattern) is with the company two up, one back template.

Figure 18.   Platoon Locations.

Figure 19.   Pattern Recognition Scoring – Two Up, One Back.

SCORE vs. Echelon Left Template — TOTAL SCORE: **29**

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	1	2	2	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	1	2	3	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	3	3	2	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	3	3	2	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 20.   Pattern Recognition Scoring – Echelon Left.

Note that the template is adjusted in each case for the highest possible score against that particular template.   The platoon itself doesn't move, but the template is adjusted so that its highest scoring cells are positioned over the platoon locations.

SCORE vs. Line Formation Template — TOTAL SCORE: **29**

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	3	3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	3	3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	2	1	1	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 21.   Pattern Recognition Scoring – Line Formation.

This score and formation type are retained for comparison with future updates. As reported vehicles adjust the locations of platoons, then the process is re-iterated from the beginning and updated assessments are provided if the new information indicates that a different deployment pattern is more likely.

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IV. APPLICATION

A. SYSTEM IMPLEMENTATION

Implementing the RETINA system in support of a constructive simulation exercise would be premature at the time of this thesis. Implementing RETINA's concepts and design methodology in a commercial product for a future simulation is appropriate and worth investigating. In the authors' opinion, the concepts described herein could be implemented in a fully functional terrain analysis and force allocation software system within several months of a decision to proceed.

In this chapter, I'll briefly describe some of the major implementation issues yet to be accomplished before this system could be described as fully integrated and complete. Assuming that the using programmer would include a variable method of reading in Digital Terrain Elevation Data (DTED) to be more flexible than the current manually entered latitude and longitude data, and that military tactical experts had prepared and validated the desired doctrinal deployment patterns for a number of tactical forces, the significant implementation tasks before RETINA (or a product with similar methods) could be of practical benefit are: 1) Improvements to allow fluid simulation of large data sets in real time, 2) Completing an agent-based program to adjust the general template to the terrain, 3) Implementing efficient comparison mechanisms for reported forces, and 4) Designing an output protocol to communicate the relevant information to a military commander and his staff.

B. FLUID SIMULATION OF TERRAIN IN REAL TIME

For the large NTC terrain data set prevalent in many of the pictures from Chapter III, the terrain data set consists of 720 x 360 elevation posts – or 259,200 separate elevation posts, each with its own coefficient of fluid transfer. While this volume of data makes the fluid simulation very sensitive to the specific nature of the terrain (note the subtle folds in the terrain from the gradient magnitude figure below), it also has the net effect of reducing an elegant, simple solution to a tedious computational exercise as we were required to run the fluid exchange program for hours in order to obtain a fluid system which has achieved equilibrium (and can thus provide reasonable avenues of approach).

Coarsening the grid by averaging the values for a block of terrain posts saves considerably on computation time and appears to provide a reasonable estimate for the most likely avenues of approach; the red lines representing the top 20% of fastest routes were remarkably similar to those of the fine grid solutions.   Estimating secondary avenues of approach using a coarsened grid is a challenge, however, because the terrain grid will now misrepresent smaller terrain features in potentially misleading ways Less of a problem when averaging Go and Slow Go terrain, or at edges between long stretches of Go and No Go terrain, the problems arise at places which were formerly classified as impassable but now appear to be simply Slow Go. Less likely to occur in the high speed avenues of approach, it's almost guaranteed to occur in the slower speed avenues of approach. To appreciate this difference, compare the results of a fine terrain grid's avenues of approach below with those obtained by a $1/16^{th}$ size terrain file (each cell representing 4 x 4 elevation posts from the original data set).   Note how the preferred avenues of approach (bottom half of each figure, in red) are very similar, but the secondarily colored lines have some interesting discrepancies in the left-most third of the figure as they traverse the congested terrain at the end of the long valley.
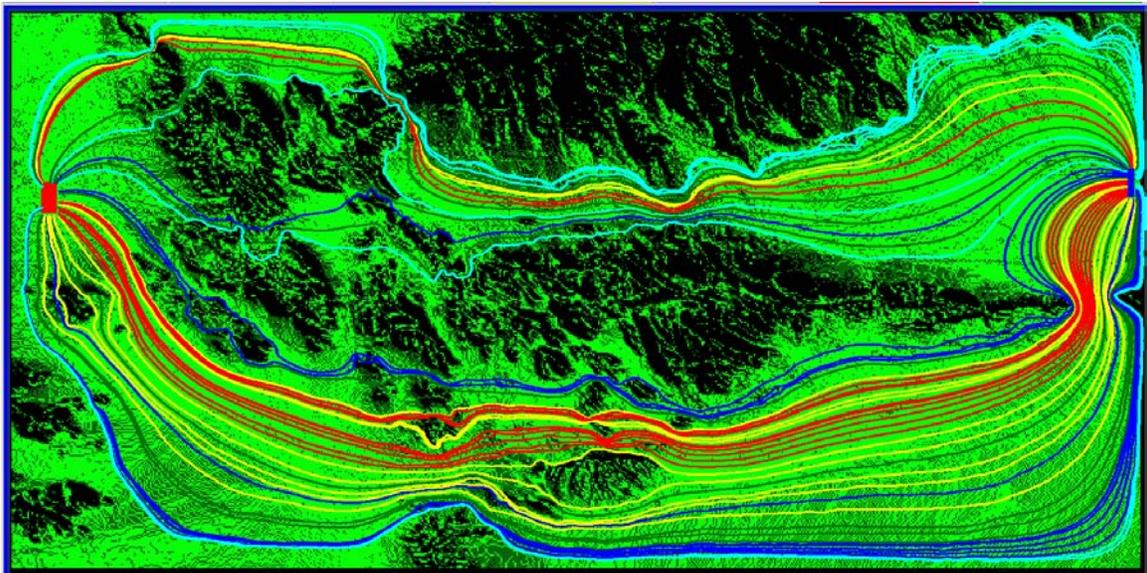
Figure 22.   Fine Terrain Grid Avenues of Approach.
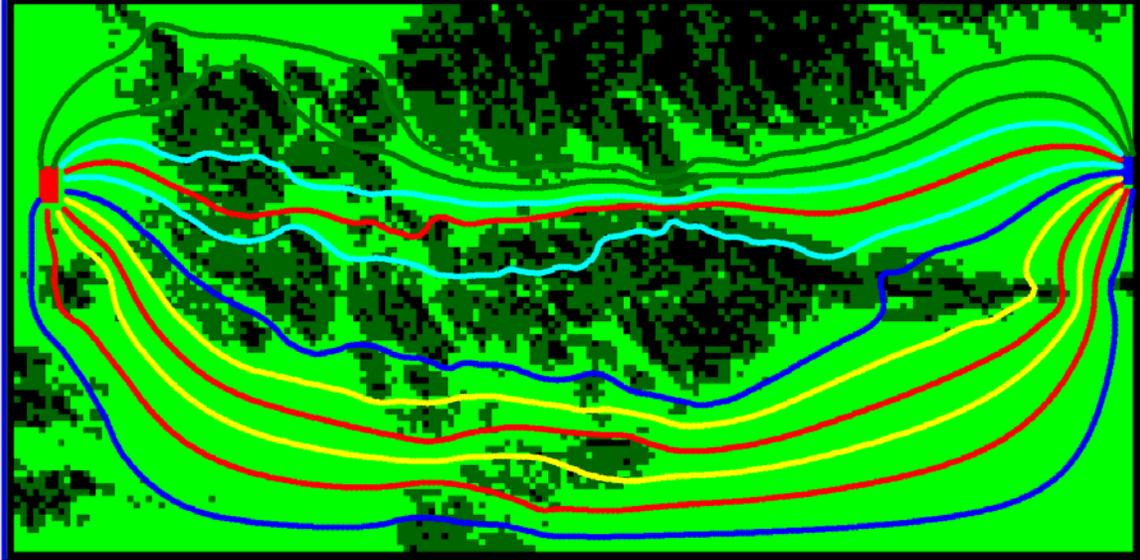
Figure 23.   Coarse Terrain Grid Avenues of Approach.

Without further testing against a specific requirement, it is difficult to state the significance of differing performance on a fine grid versus that on the coarse terrain grid, but it seems worth noting that the fine grid solution, while preferable for its results, is not viable for real-time analysis in its present configuration. Route calculation in real time is trivial, but achieving simulated gaseous equilibrium in a 300,000-cell terrain grid is laborious and must be improved before this program is ready for commercial export.

It's reasonable to assume that there are suitable techniques for decreasing the amount of time to achieve a uniform fluid distribution based on the distance of each cell from the source and sink. This would produce a very rough approximation of dispersed fluid volume but perhaps reduce the time to produce equilibrium with consistent gradient vectors considerably. Using DTED Level 1 data would similarly reduce the data set to a more manageable size for real-time processing, but would be subject to the same loss of subtlety evidenced in the coarse terrain grid above.   Balancing processing speed with degree of required resolution warrants further study prior to an implemented solution and, though identified here, is not further investigated in this thesis. Using the result of the coarse simulation as an initial condition for the fine one is an obvious and easy to implement approach. Because of the equivalence to linear system solution noted above, there are no end of techniques to try here.

C. AGENT-BASED PROGRAMING

The proof of concept HGHC agent program discussed earlier in this work provides a rough structure but little useable code for a robust program to evaluate the competing goals for each platoon-level unit as it self-adjusts on the terrain set. The useful concepts for implementation are a full understanding of the tension which exists at each echelon of deployment between the various goals. This concept must be incorporated into any finished product in order to even roughly equate the process with that experienced by humans in the real world. For added clarity, this tension is illustrated below.
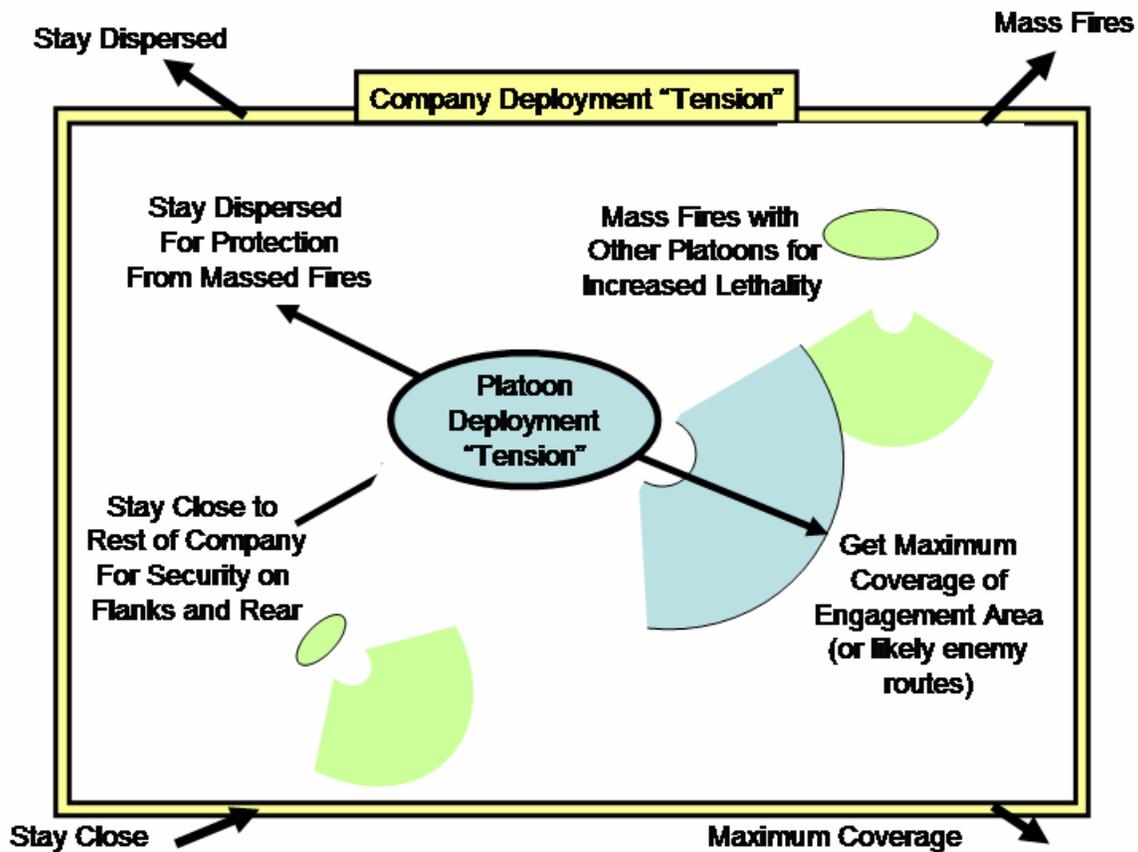
Figure 24. Platoon Deployment Goals.

This process occurs throughout the military at each echelon of command. Leaders balance the requirements to close with the enemy and mass fires against equally important demands for protection and security in order to accomplish their missions. At each echelon, the leader makes a rough assessment of these factors and assigns a general deployment location to his next lower unit. This lower level leader conducts an almost

identical assessment, but on a smaller terrain set, with reduced number of forces, and a higher level of resolution. In real life, the process ends when the individual vehicle commander lies prone on the ground to confirm line of sight angles before giving the approval for engineers to begin digging the fighting positions. In this program, we conclude at platoon level as it's assumed that individual vehicles will be reported via updates from the simulation and do not need to be templated at that level. If required, one could easily include this level of resolution by adding one of the many available line of sight estimating software packages.

In paragraph A of this chapter I briefly mentioned an assumed set of deployment templates. Speaking strictly in terms of time and level of detail required, producing this library of doctrinally correct military templates for a wide variety of organization types and sizes will be a considerable amount of effort. This is all documented and fairly widely known information, but producing these templates in useful digital format is yet to be completed. It is likely that one could save considerable time by employing flexible template patterns which use combinations of lower level templates held together by average distances and degrees of confidence to form the larger templates, but even this approach will be a largely manual process of defining combinations of templates required for many different types of units. At first guess, the right order of magnitude for this effort would be defining two or three different Armies, each with 3-5 different types of Divisions, each with 6-10 different types of Regiments and separate Battalions, each of which will have 6-10 different types of subordinate elements, and each with at least three different movement templates and 1-2 defensive deployment templates.

D.   DESIGNING EFFICIENT COMPARISON TOOLS

Rapidly cycling through potential deployment templates as described in Chapter III will require a very human-like programming implementation of layer-by-layer data survey to confirm or deny our suspicions (or, in this case, the templated simulation force locations) before deciding to investigate further at a higher level of resolution.

Evaluating every new reported vehicle against the possible changes across the front will quickly consume our resources without ensuring that there are established thresholds for each assumption above which we can accept some uncertainty.

For example, if our application of the deployment patterns indicates that we've identified two platoons deployed as part of a company echelon left formation, we accept that this decision comes with a minimum of one platoon's worth of uncertainty. Given this, the report of a single vehicle within the overall deployment pattern of a company but which does not fit within our estimated third platoon's location can cause us to either 1) cycle through every possible company template to see if there are others with higher percentage of accuracy, or 2) acknowledge that the vehicle is part of the same company (within the footprint of a company) but that it doesn't match what we expected to see, perhaps by degrading our confidence rating of the assessment.

I believe that the latter approach is a more accurate representation of truly human-like pattern recognition as described by Klein in Sources of Power. According to Klein, human experts don't cycle through continual analysis of options as much as they continually evaluate cues, indicators, and warning signs to either confirm or deny the validity of the selected course of action. Although it's certainly possible to cycle through the small list of potential company deployment templates to identify templates with potentially higher scores, doing so for every unknown new vehicle (often this number is in the thousands for larger scale simulations) seems to be inefficient, at the least. Using cues and threshold values will allow much more run-time flexibility while preserving both the principles of Recognition Primed Decision-Making (RPD) as well as the integrity of our estimated situation. Implementing a computer vision pattern-matching program for assessing potentially thousands of reported digital entities will be extremely challenging without incorporating this concept of threshold values, sensors, degree of certainty, and variable resolution monitoring from the outset.

E.   **REPORTS TO THE USER**

Not discussed previously in this thesis, the final stage of RETINA is the most visible; its output to the training audience. A fully implemented solution would include a number of reports, diagrams, charts, and digital overlays to fully convey the interpreted information to its intended recipient. The art of inferring military intent from the actions and movements of icons on a screen has regrettably not been addressed by the author due to lack of time, but is worthy of its own dedicated research effort.   Without this critical product, RETINA's ability to report intentions and to conduct assessment based on

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reported actions of a thinking commander is severely limited.   As such, Commander's Situation Reports (SITREPs), and Intelligence Reports (INTREPs) are not within the scope of this thesis.   In order to produce these reports and this type of output, the user will be required to expend considerable effort translating physical movement patterns into indicators of intent. Some of these are fairly simple (for example, a unit in column formation does not expect to encounter the enemy), while others are more complex, but as none of those linkages are investigated in this work, those outputs are deferred for follow-on researchers.

The concepts discussed in this thesis will produce an adequate assessment of terrain, conduct a limited assessment of likely human movement through that terrain, and infer likely defensive positions for a similarly-minded tactical force intent upon defeating the moving elements. These concepts are highly visual in nature, and best communicated by visual methods. Current protocols are a combination of annotated images and paper or digital map products and overlays. Converting the information available in this architecture to those media is easily achieved on an automated or man-in-the-loop fashion. Advances in three dimensional imaging tools make this an attractive option as well, and the same data elements that produced the 2D avenues of approach could be converted to produce a 3D visualization of an attack during the wargaming process.

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V.   TESTING AND ANALYSIS

A.   EVALUATING EFFICIENCY IN ROUTE SELECTION

Further study of human path selection is required in order to confirm that the intuitive benefits of the results obtained above for predicting most likely avenues of approach are supported by human experimentation.   This comparison was not conducted prior to completion of the thesis, but is acknowledged to be required before the fluid simulation can be categorically proclaimed an accurate representation of human path selection or wayfinding tendencies.   RETINA avenues of approach are compared to an A* search with generally desirable results.

1.   A* Search Comparison

Comparing the results of RETINA fluid simulation optimal routes with those produced by an A* search pattern confirmed that RETINA's routes are, as suspected, not optimal traversals of the terrain grid in terms of pure time to traverse each cell between source and sink.

The parameters of my search comparison are as follows.   For both the A* and RETINA route selection the cost factor is time to traverse from start to finish. Specifically, time for the route from one node to the next is computed based on the distance between nodes divided by the maximum allowable speed at the next node.   To traverse ½ of a cell which can support 25 kilometers per hour traffic (or maximum speed for this model), given that each cell is 30 metes from the next is calculated as 15 meters divided by 25,000 meters/hour, or 0.036 minutes.   Routes for both RETINA and A* search pattern are computed based on a start point which is one cell away from the Source location and an end point which occurs the first time the route is less than 1.5 cells from the goal (or Sink). A* calculations use a cost function of cost to date (along the given set of previous points) plus a heuristic of straight line distance divided by maximum speed.

Some results of this comparison for small sample data sets are depicted in the table and figure below.
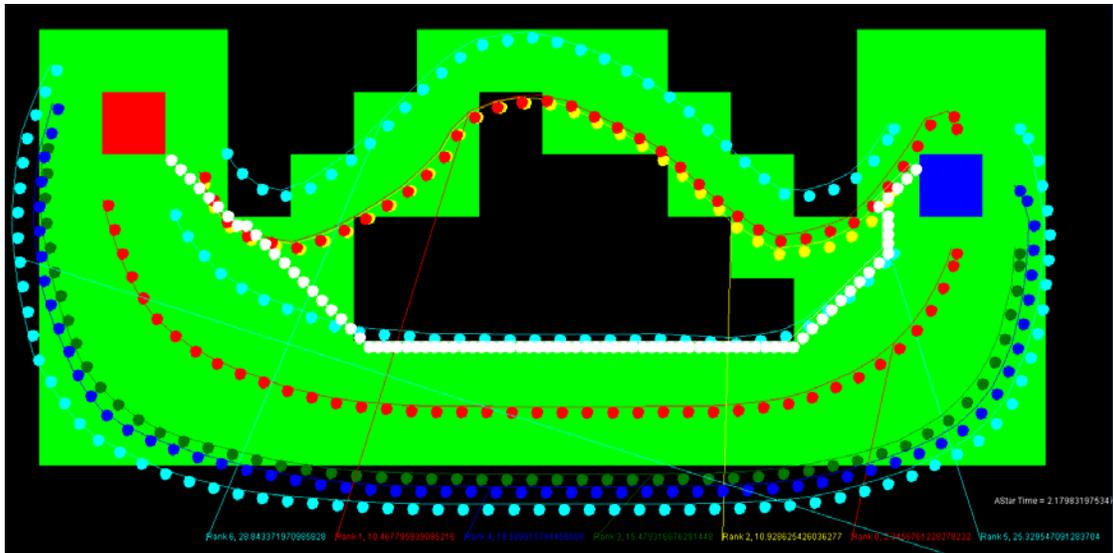
Figure 25.   A* Route (White) vs. RETINA Route (Red).

Best A* Route	Best RETINA Route	Difference
11.272779	11.735077	104%
14.030301	21.354893	152%
14.937777	18.820330	126%
5.408957	5.974708	110%
5.507293	5.974708	108%
5.507293	5.974708	108%
2.086014	2.345676	112%
2.200198	2.345676	107%
2.225082	2.345676	105%
2.179832	2.345676	108%
2.258825	2.345676	104%
	AVERAGE Time Difference	113%

Table 3.   Sample of Results from A* Compared to RETINA.

From the table above its obvious that there is significant variability between truly optimal routes and those selected by the fluid simulation as most likely routes. These results were obtained from a limited number of small terrain samples such as the one shown in the figure immediately preceding the table. The highest variability occurs for those sample sizes which I created with multiple twists and turns along the shortest path and wide paths to the outside.   This is quite similar to the route through a major city, technically faster by driving more direct path through the city given no traffic delays, but with a preferred route on the high speed beltway around the city. See the figure below for an example of this effect. As with other figures, the A* routes are indicated in white,

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and the preferred RETINA routes are indicated in the order Red, Yellow, Green, Blue, and Cyan.
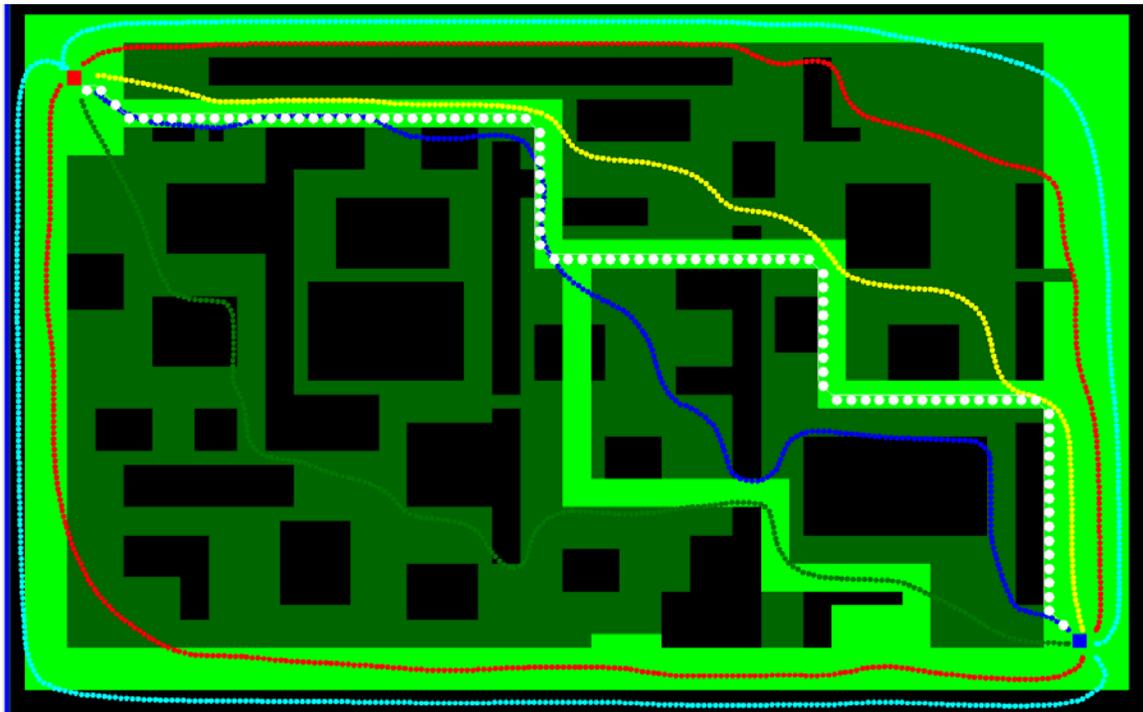
Figure 26.   Another A* Route vs. RETINA Route Comparison.

2.   Faulty Assumptions

Comparing A* search pattern results with RETINA optimal routes may seem to indicate that a more efficient method of producing the best avenues of approach between two points would be to use an A* search of the grid. This assessment would be incorrect, for the search comparison is based on two flawed assumptions: 1) humans would choose the optimal solution, and 2) the A* search above reflects all appropriate costs.

a. Humans Don't Choose the Optimal Solution

Cognitive studies are required to confirm the author's belief that large military formations do not select optimal paths but rather something much closer to a path of least resistance within the bounds of the higher level commander's stated intention and general movement guidance. I maintain that even when producing most likely routes which are unconstrained by a set of higher commander's orders the analyst must recognize that humans do not make navigational decisions based on optimal path planning. Factors such as ease, speed, amount of turns, confidence in selected route, and

navigational aids all combine to produce traffic patterns which are decidedly not optimal. Whether describing military formations of large numbers of vehicles or the individual decisions of a single vehicle on an isolated grid, the author asserts that humans are more likely to follow something akin to an easiest path or simplest path algorithm rather than choose the mechanically optimal, or shortest path, route.

Many of the above assertions have been observed and are discussed in published works relating to traffic patterns, to include Duckham and Kulik's discussion of Simplest Paths. Specific cognitive analysis of military unit movements across terrain and of single vehicle driver decisions in varied terrain (both off road and on existing road networks) are required to confirm the author's specific assumptions.

b. Ignored Costs

A second flaw in our A* search is its ignorance of the laws of physics. Real human beings (and real vehicles) are bound by laws which impose physical costs (in terms of time) for changes in direction, stops, starts, and time to achieve maximum speed. We cannot achieve instantaneous speed changes and similarly do not make changes of direction at constant speeds. A more detailed comparison of RETINA's avenue of approach results should include cost factors for changes of direction, changes in maximum speed, turns, and stops required. These costs are significant in the real world, and if modeled in our cost comparison would surely lead to a reduced gap between the optimal mechanical solution and the optimal RETINA-produced fluid simulation solutions.

3. Considering Military Units versus Single Vehicles

One significant set of factors not discussed previously in this thesis are the attributes of military units versus those of a single vehicle. Military unit movements can be characterized with a width, length, expected turning radius, and likelihood to change direction which are all different than those of a single vehicle. Additionally, the speed factors for a multi-vehicle organization are different than those of a single vehicle; acceleration, turning speed, maximum speed, time to decide on route change, and deceleration can all be expected to be different for a larger element than for a single vehicle. These factors are not defined by this research but are believed to weigh significantly in favor of a fluid-based simulation as method of computing routes versus a

computational geometry approach discussed in Chapter 2 or the A* optimal path described above. In the opinion of this author these factors combine to produce the effect described as following the path of least resistance, or path of least action. As the size of a unit increases above a single vehicle, one can reasonably infer that its likelihood of following the simplest route would also increase due to the increased difficulty in changing the route of a larger unit. Whether specifically defined in terms of the factors described above, or characterized more generally as organizational inertia, larger units tend to travel in smoother paths which resemble those generated by RETINA much more than the optimal or shortest path routes produced by other methods.

a. Considering Unit Width

This section would not be complete without another brief discussion of military unit width. Military units travel in a number of different formations based on size of the unit, likelihood of enemy contact, and desired speed. RETINA assumes that a unit must travel from the source to the sink and computes the most likely routes based on a number of identified start points. If we assume that the unit must travel from the source to the sink, then RETINA's most likely avenue of approach is valid regardless of preferred unit width because the RETINA-generated most likely route will also be the route which supports the highest total flow volume from source to sink. In general, military units will compress to a width narrower than the described "normal" or doctrinally prescribed width for short periods of time in order to achieve a high overall traversal rate.

Considering military unit width as a fixed number (below which a route is not possibly traversed by the unit in that formation) is a mischaracterization of the real movement tendencies of a military unit and one of the reasons that RETINA's routes are superior to those obtained by computational geometry. Admittedly, one could assign a width plus some degree of flexibility or willingness to shrink and thereby obtain a more realistic picture of potential routes with purely geometric route selection tools. Doing this will only help define the total possible routes, and will say nothing about most likely routes unless one assumes a combination of shortest path among the reduced set of width-supportable routes with some likelihood of willingness to shrink unit width to accommodate each route under 100% of desired width.

It is possible to overlay a unit width requirement upon RETINA's results to eliminate the "impossible" routes. Conceivably, some of the most unlikely routes generated by RETINA would include "impossible" or improbable routes for units of greater than single vehicle size. In the author's opinion, this is not required. If one accepts the proposition that the unit must travel from source to sink within the bounds of the identified terrain sample, then RETINA will generate the most likely avenues of approach for easiest movement between source and sink. In the case of several small obstacles which break up the movement corridors to less than desired deployment width, it is the authors contention that the military unit will choose "easiest" over a prescribed doctrinal width, just as a stream will continue to flow through a rocky section if the smooth streambed is too far out of the most natural path. Shown below are two use cases to demonstrate RETINA's approach to narrow terrain corridors, in both cases the optimal route is the most efficient traversal; once through the narrow corridors and once using the wider corridors.
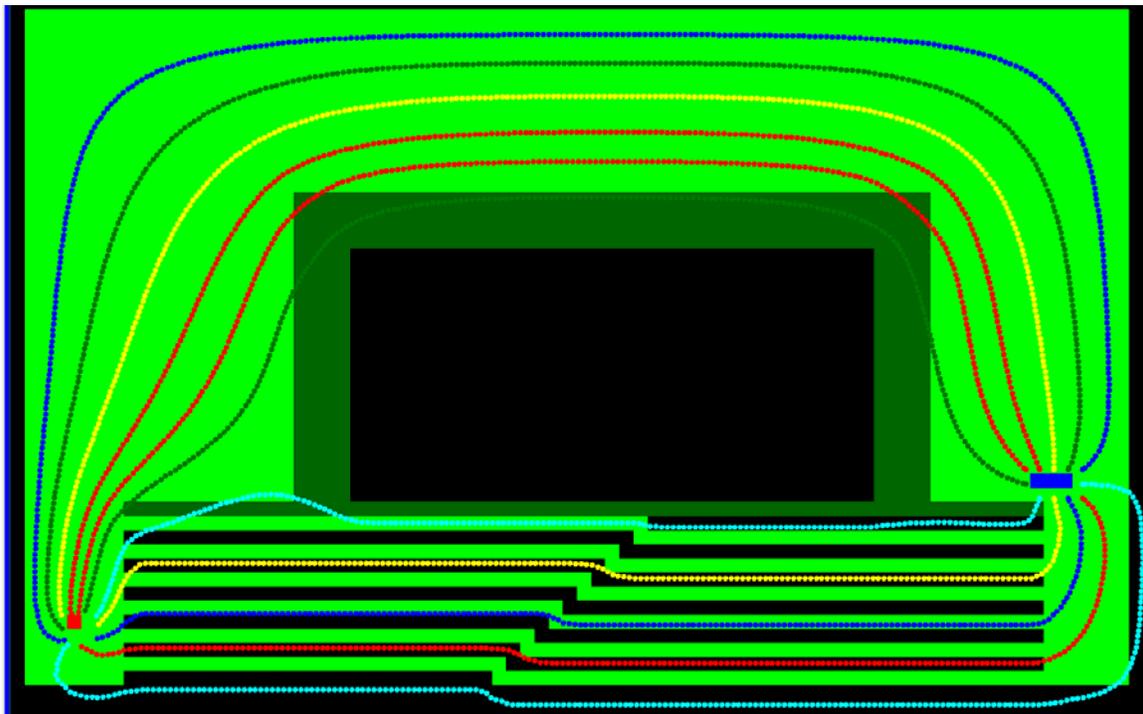
Figure 27.   Most Likely Route through Wide Corridor.
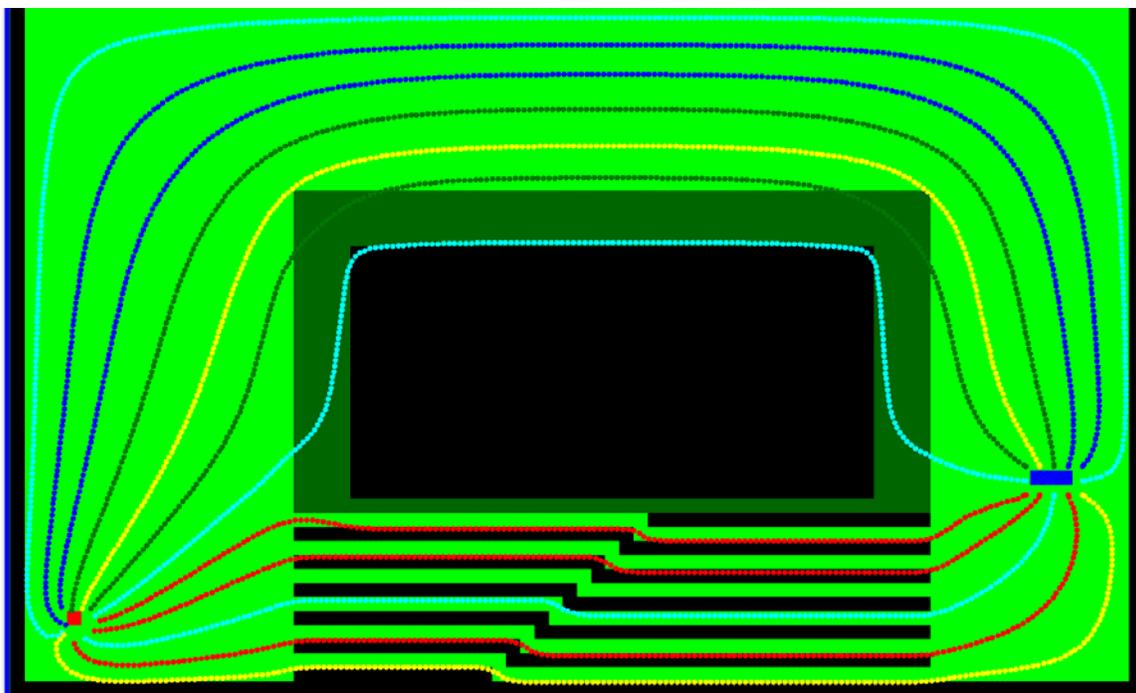
Figure 28.   Most Likely Route through Narrow Corridors.

Note that for the figure above the only difference is that the avenues of approach spend less time in the more restrictive terrain, so overall it's a preferred route to the wide corridor above.   This seems consistent with a military unit's willingness to break up a formation to flow around several small obstacles provided they are able to quickly rejoin the formation on the other side. If the obstacles and congested areas are too big, however, it becomes easier to go around rather than pass through the congested terrain. This is shown on the previous figure.

4.   Comparing RETINA to Human Analysts

Described below is a study intended to evaluate the deployment algorithm's utility when compared to the opinions of military terrain experts deploying a mechanized military unit at the NTC. As part of this process, these experts produced avenues of approach when they considered potential enemy actions prior to deploying their defensive units. Though these routes were not recorded in sufficient detail or quantity for deliberate analysis as part of this thesis, it is interesting to compare the routes from this experiment with those produced by the fluid simulation.

A visual comparison of the routes selected by our military terrain experts shows that those routes are strikingly similar to the optimal routes indicated in red from

Figure 23 (the Coarse Terrain Grid Avenues of Approach) and vary only slightly from those in Figure 24 (the Fine Terrain Grid Avenues of Approach). It is interesting for two reasons: first, because these figures appear to face validate the fluid simulation as a method of modeling avenues of approach; and second, because its interesting that the humans, when told to produce estimates in a very short time, made the same assumptions about exits from the northern valley which occurred with the coarse terrain grid. They both assumed that the best exit from the northern valley (called the Valley of Death by NTC personnel) is by proceeding directly West over the Slow Go terrain whereas the fine terrain grid indicated that the optimal exit from the Valley of Death is to the North West of the valley (near the Fort Irwin Airfield). With further study one could argue that perhaps both estimates (the hasty humans and the coarse terrain cells) suffered from the same problem of over-generalization. It would also be of great interest to compare these results with the results of real human individuals and larger military units.

B.   COMPARING DEPLOYMENT PATTERNS

In order to produce good and reasonable estimates of where an enemy force will deploy, we make several assumptions. Foremost in these assumptions is that the enemy force will interpret terrain in roughly the same manner as that of our subject matter experts for this thesis and of the study group for follow-on cognitive studies. This is an important assumption which cannot be overlooked. The military aspects of terrain (Observation and Fields of Fire, Cover and Concealment, Obstacles, Key Terrain, and Avenues of Approach) are all assumed to be based on the physical truth of geographic information about the terrain or upon the weapons characteristics of friendly forces. Recent interest in cross cultural modeling challenges may result in information which indicates that selection of Avenues of Approach should be modified based upon the knowledge and cultural background of the modeled opponent, but for purposes of this work the enemy is assumed to have an equal appreciation for the military aspects of terrain and, equally important, to share the assumed predisposition to select routes similar to those proposed by the RETINA fluid simulation. Based on this assumption, I was able to consider the beneficial aspects of terrain from both the offensive and defensive points of view and represent the best known effects without regard for cultural differences. I assumed that U.S. military expert opinions with respect to avenues of

approach are also valid when considering the approaches of other national forces, and used U.S. terrain expertise to consider both offensive and defensive factors without regard for national tactics or doctrine. National doctrine is reflected only in the actual deployment templates, but not in the areas of code or thesis regarding appreciation of terrain itself.

In December, 2002, the author conducted a limited scope human factors experiment to determine the most important planning factors applied by military terrain experts when emplacing a defense. I produced a brief military situation and planning map to seven U.S. Army and USMC officers with experience analyzing terrain for military applications and recorded their thoughts and insight. While not a statistically significantly sized study, the insights gained were valuable in directing further research direction and refining the deployment algorithm and are presented in shortened form here.

1. Conditions and Task

The only information available from a DTED terrain set is an array of elevation posts. I tried to mimic this minimalist amount of information in the experiment by only providing a plain black and white map with elevation and road networks annotated.

Subjects were briefed verbally that they would have a short time to study the map, then quickly array one Battalion Task Force on the map to defend Fort Irwin against an attack from the West by a Motorized Rifle Regiment (MRR). I asked the subjects to verbalize their thoughts as they emplaced forces on the ground explaining why they selected a particular piece of terrain. Subjects deployed 4 companies (1 Tank, 3 Mechanized), one Mortar Platoon, and 5 Scout Sections. Their defense was enemy force oriented (destroy the attacking MRR) in order to protect the town of Fort Irwin. Subjects were given complete freedom of maneuver and employment confined to the limits of the map sheet. Finally, they were told not to consider the northern 2KM of the map sheet but to assume a friendly unit would defend North of Teifort Mountain.
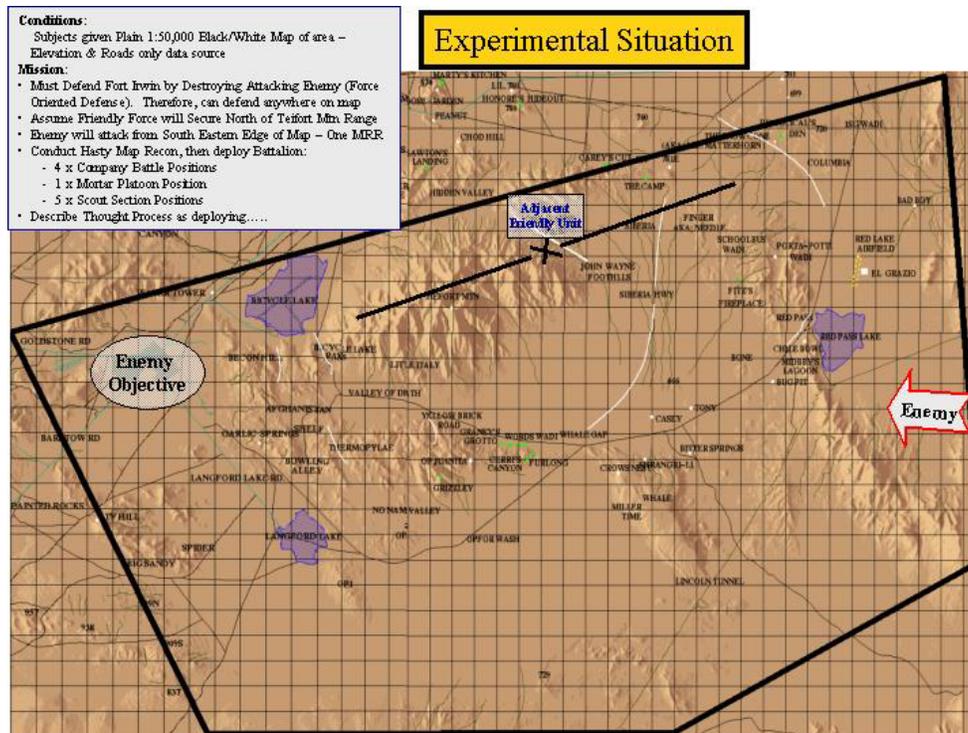
Figure 29.   Portion of Terrain Map Provided to Test Subjects.

2.   Possible Avenues of Attack

The figure below represents the combined assessment of the author and the seven military experts from the study. Each assumed the avenues of approach displayed on this picture as part of his planning process with very minor differences. This figure eventually became the standard by which I measured various path finding or avenue of approach generating methodologies, and it was by studying this chart in detail that we began the search for a fluid-based avenue of approach generating tool.
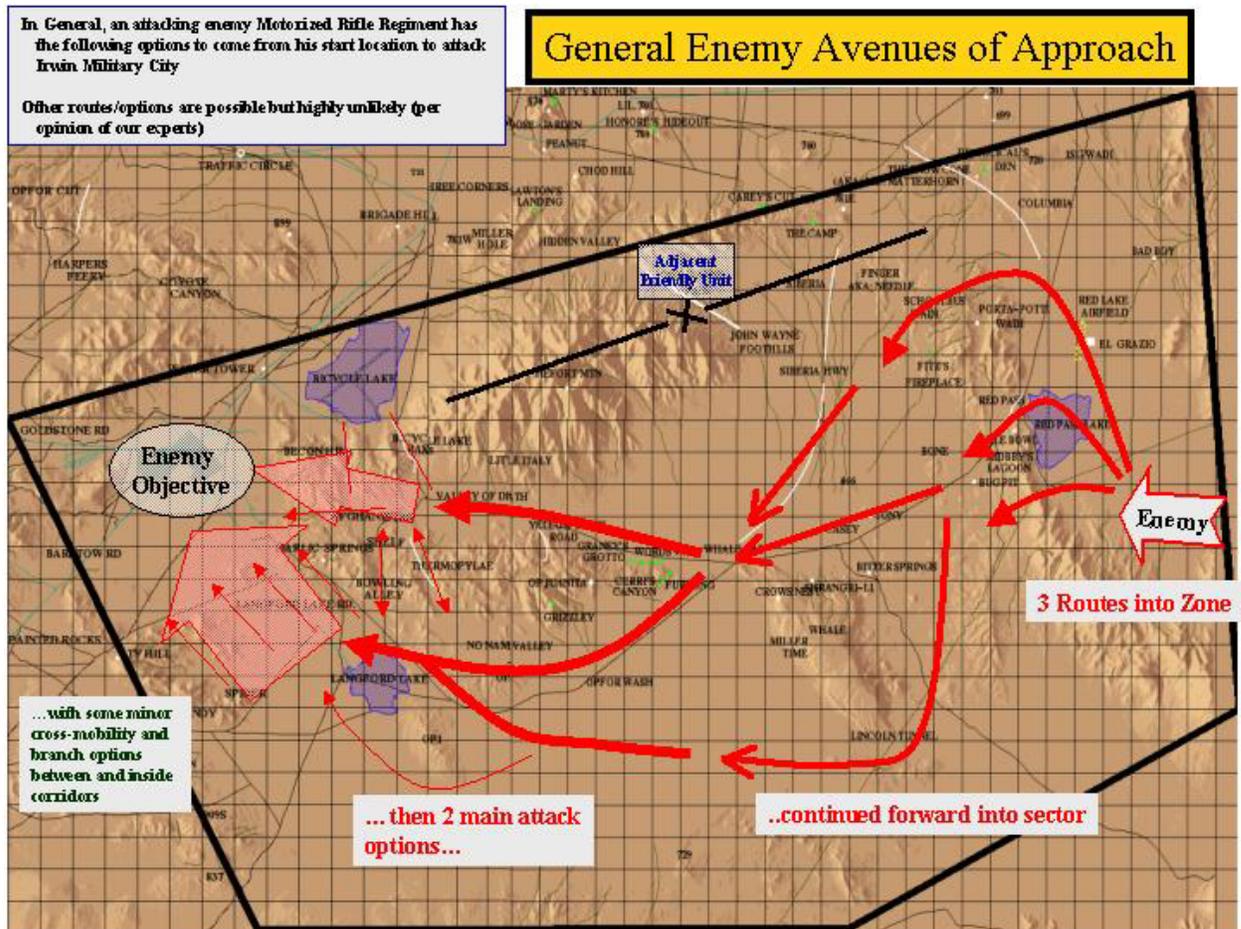
Figure 30. Avenues of Approach Generated by Terrain Experts.

3. Defensive Deployment Schemes

I expected that the results of several experts analyzing terrain would yield surprisingly similar selection of company battle positions and battalion engagement areas. This expected consistency did occur, however not in the manner that I'd envisioned. In general, subjects tended to think in two completely different directions: objective-focused or enemy-focused.

a. Objective Focused Defense

The objective-focused defenders all deployed forces a the first, best terrain locations forward of the briefed enemy objective, Fort Irwin. They picked remarkably similar company battle positions, scout locations, and mortar platoon locations for a defense oriented towards what they believed to be the most likely enemy attack at the last

good place to defend (before the terrain opened up to the open ground surrounding Fort Irwin. These defender's results are show below.
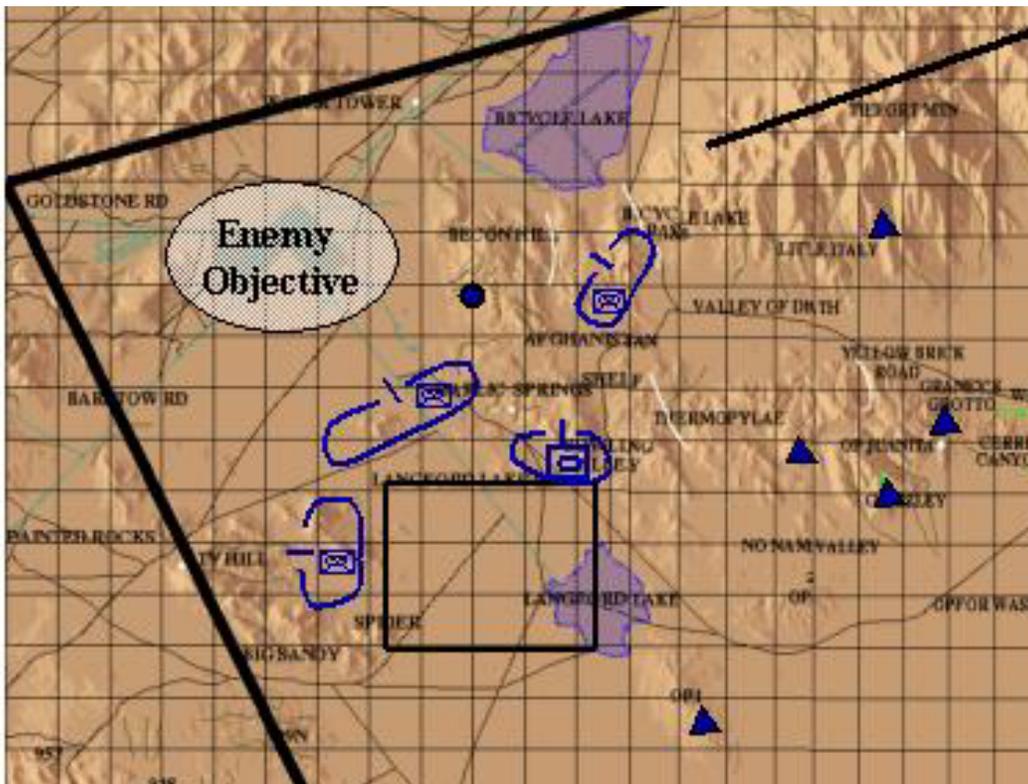
Figure 31.   Subject 4 Defensive Array.
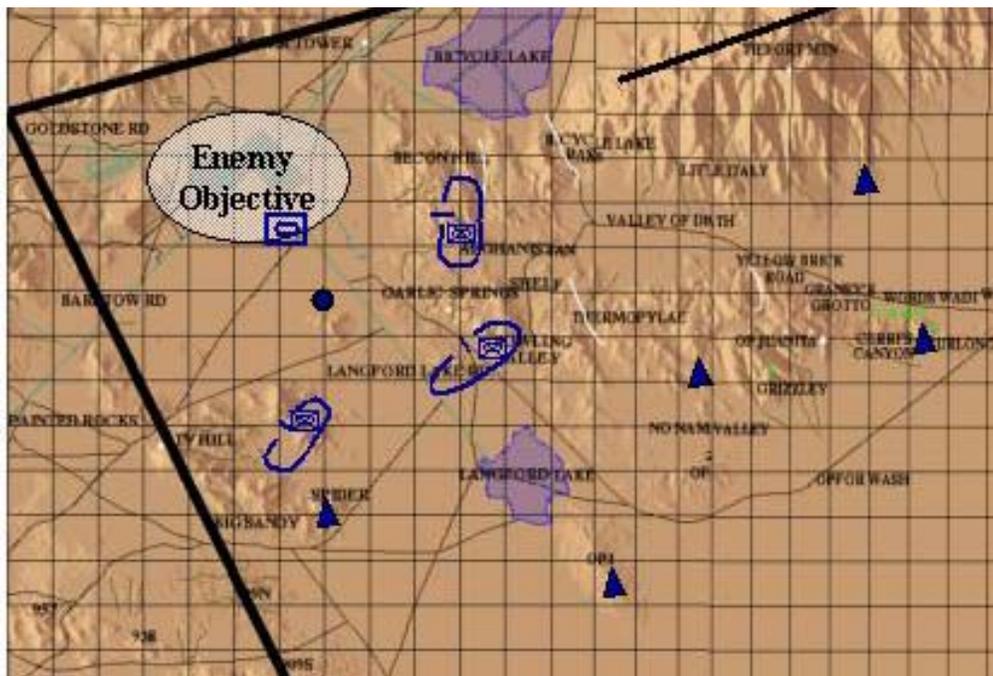
Figure 32.   Subject 5 Defensive Array.

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Note how both of these subjects anchored their main battalion engagement area with a company on each shoulder and positioned a third company along the less likely attack zone to the North (along the "Valley of Death") as a defense against this less likely (and potentially more dangerous) course of action. Also note that both positioned Scout sections in relatively close proximity with the purpose of confirming the anticipated most likely and most dangerous Courses of Actions (COAs).

I should note here that this approach to Scout section employment was universal for all subjects. No subject really spent much time on particular Scout locations as much as they indicated a "..looks pretty good" location from which they also communicated the intent or purpose of the scout at that location ("…he ought to be able to see them come thru the pass from there.."). There are other, more specific, comments about scout section employment, but in general the attitude was one of assigning a purpose and place to observe rather than assigning a specific place to be. This approach is consistent with the established U.S. Army tactics and techniques for scout employment.
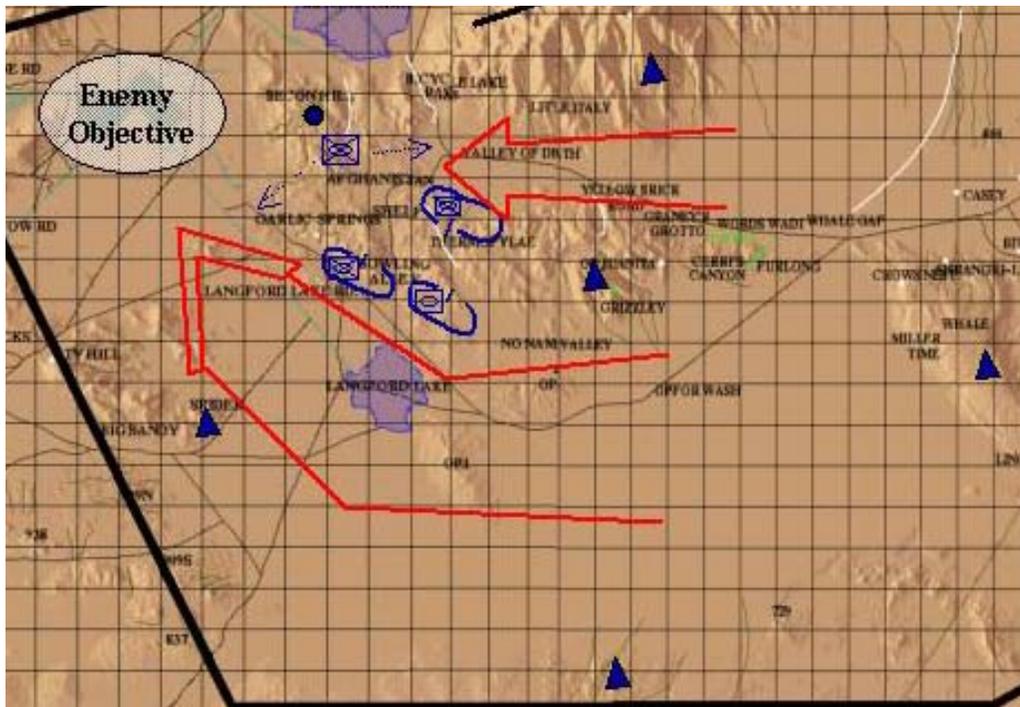
Figure 33.   Subject 6 Defensive Array.

Subject 6 is an interesting variation on the theme of Subjects 4 and 5 in that he arrayed two companies side by side on the right shoulder of his anticipated main attack and left the left shoulder completely open for enemy advance. On reflection, however, he then added the Scout section on the left shoulder of the potential enemy attack and a counterattack arrow from his reserve unit (in the center near the mortars) to "balance" out the defense of that portion of his sector. It's almost as if our subject recognized the unbalanced nature of the defensive scheme after it was complete and made the final revisions to his array to compensate for this tactical mistake…at least visually.

b. *Enemy Focused Defense*

Whereas the objective-focused defenders chose options in defending against an enemy attacking along essentially one of two main axes, the enemy-focused subjects all shifted the map so that the Eastern edge was directly in front of them and conducted some form of mental simulation of enemy attack options from the moment he entered the map. Some conducted very detailed attack route analysis (one drew a sketch in pen on a blank sheet of paper) and others just traced the routes on their map with a finger, but all began their analysis at the earliest possible edge of the map. In fairness to the objective-focused defenders, some of them conducted the same assessment before concluding that the earlier options were not relevant to the best place to defend…and that at the best place(s) to defend there were only two main attack options. Our enemy-focused subjects were much less willing to yield that much freedom of maneuver to the enemy and all formed defensive schemes well to the East of subjects 4, 5, & 6. Their defensive schemes are indicated below.
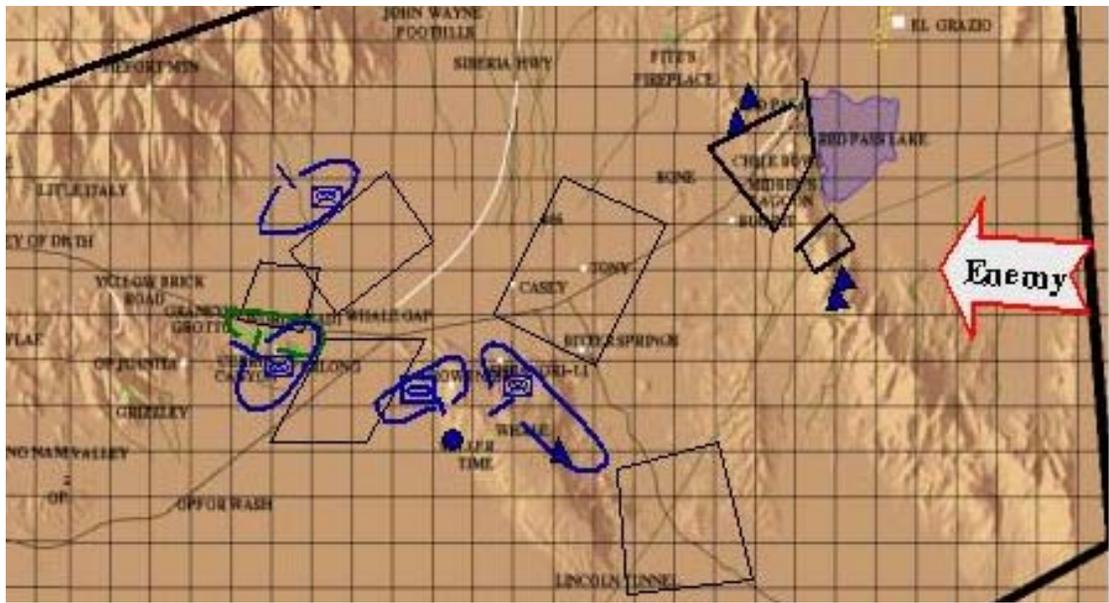
Figure 34.   Subject 1 Defensive Array.
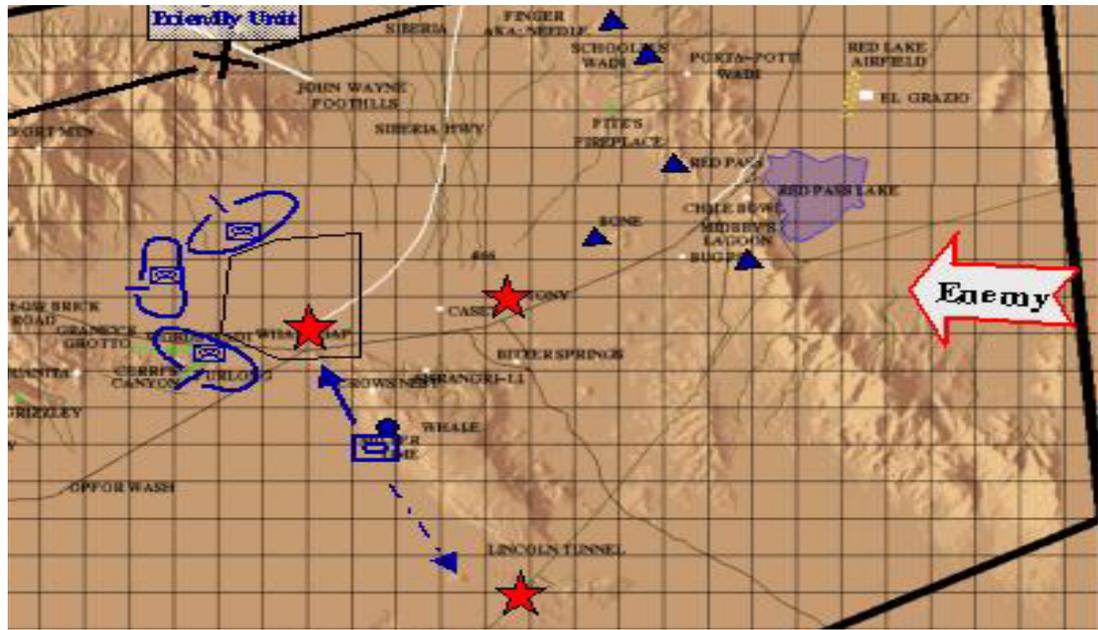
Figure 35.   Subject 2 Defensive Array.

Subject 2 conducted a very detailed enemy AA assessment before selecting three key areas where the enemy commander was forced to make a decision (indicated in red stars) and concluded that the best location for a friendly battalion engagement area was as the enemy decided to commit due West (into the Valley of Death) or Southwest (towards the Langford Lake approach).   He then anchored his defense to destroy the enemy at this location and used is Tank company reserve to either

complete destruction or to stop an enemy attack along the less likely attack to the South of the "Whale" (bottom red star).

Subject number 1 appeared to use an identical terrain analysis but chose to position one company further forward (front slope of the "Whale") and to "…mine the heck out of the southern pass (black box below Red Lake Pass) to "encourage" the enemy not to pursue the Southern-most attack axis.

Figure 36.   Subject 3 Defensive Array.

Subject 3 constructed a very mobile defense which is perhaps difficult to understand from the picture above. At its' essence, however, it is very similar to Subject 1's plan: Attack enemy early (before he comes thru the passes), then defend from the Whale area to "push" him towards the most defensible terrain North of the Whale Gap. If so, then destroy him there with 3-4 companies' worth of fire. If he (enemy) goes South, re-position South to engage just South of Whale Gap with 2-3 companies worth of fire power.

A high risk variation of enemy-focused defense planning was the approach chosen by Subject 7, who planned a defense along what he believed to be the most likely

enemy course of action as a series of company-level engagement areas rather than a larger battalion engagement area…sort of a gauntlet run for the MRR commander. This approach assumes that the enemy is very objective focused (he just wants to get by our defenses to get to his main objective), and if correct is likely an effective defense against a moving, objective-motivated enemy (similar to the "real" OPFOR at the National Training Center). The risk of this approach is that each company can become isolated and defeated independently of the others by a force-oriented enemy.
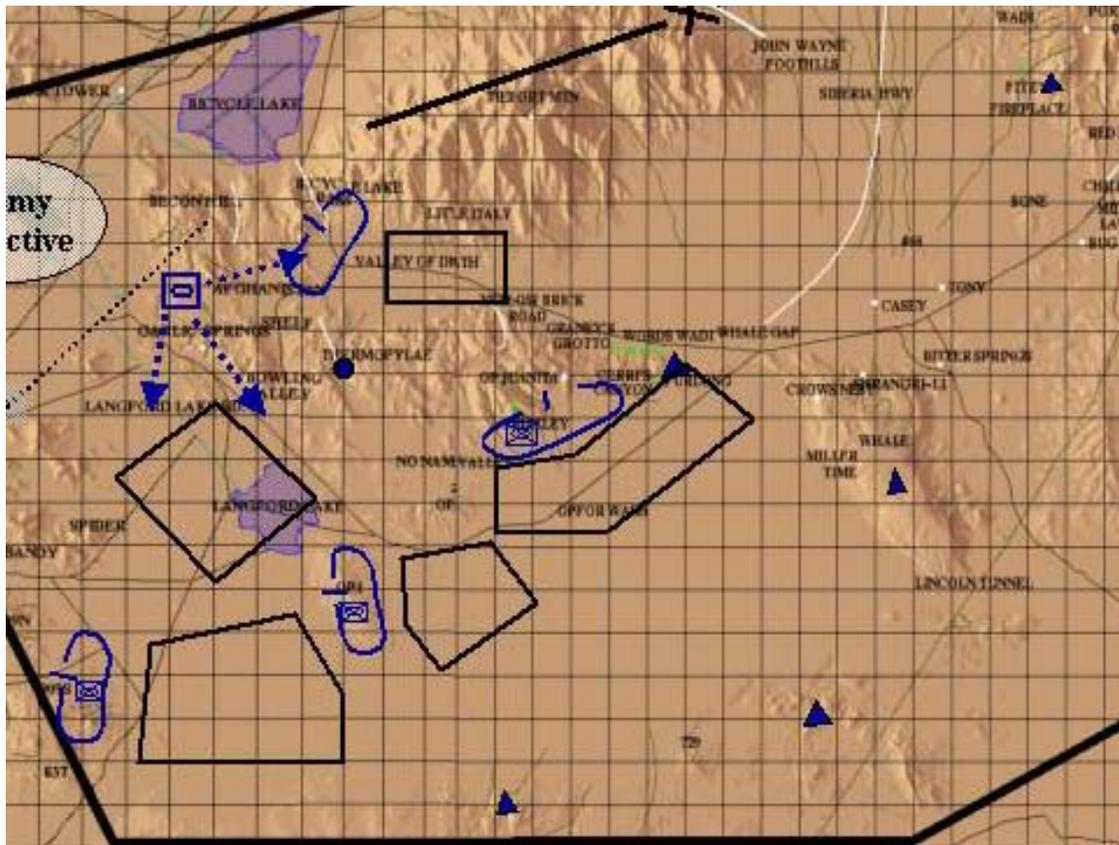
Figure 37. Subject 7 Defensive Array.

In spite of its high degree of risk, it seems appropriate to include the results of this approach because the many other pieces of this defense are tactically sound, rational, and provide good algorithmic insight for encoding positions (..Company BPs, Scout locations, Mortar Location, Reserve location). It also served as a good reminder that writing a program to "…look like a human did it…" should also include a certain percentage of designed variance from the established rules and standards for

tactical employment. Sometimes it makes sense to employ a high risk defensive plan if you know a lot about the enemy force and the way he fights.

4. Analysis of Experimental Results

The primary benefits of this experiment towards the current state of RETINA are its confirmation of Avenues of Approach and consideration of Key Terrain as the two dominant employment factors for hasty emplacement of a military force upon the terrain. Other factors weigh in after employment in a general position to produce locally optimal results after the main defensive decisions have been made based on the first two factors. This appears to confirm the RETINA methodology of considering first the terrain and viable avenues of approach, then identifying potential chokepoints or reduced option key terrain to anchor a defense, followed by an application of other planning factors within the local decision of which key terrain to utilize and which primary avenues of approach to target. Each of the objective focused experts chose to defend the most likely avenue of approach and to deny the most dangerous (by a physical presence in the "Valley of Death").

The secondary benefit of this experiment is that even though I tried to create an environment of little time (and thus instinctive employment without detailed analysis) for the experts, each of them performed a form of mental simulation as he emplaced his defense, many of them doing it out loud in phases as they envisioned what the fight would look like from their particular defensive array. This seems to reinforce the requirement to conduct a simulation within the simulation if we're truly to create a software system that replicates human thought – or at a minimum replicates human results.

C. MENTAL SIMULATION

Earlier in this thesis we discussed two shortcomings of the initial version of agent based programming designed to fine tune military deployment of vehicles and units given some start point (or anchor point) and an array of weighted terrain posts. Specifically, there is a requirement for two types of mini-simulations within the agent programming portion of RETINA. Those two requirements are 1) a simulation to compare tactical results based on variations of weighting criteria in the overall objective function, and 2)

comparison of tactical results at selected anchor point locations in order to validate the objective function.

1. Evaluating Weighting Criteria

Weighting criteria for the agent based program that refines vehicle and unit positions from a doctrinal template to a terrain based deployment are selected based on the personal experiences of the author and research into the relative merits of associated deployment factors. Adjusted with some trial and error, these weighting factors seem about right based on the results obtained during initial face value testing. There is no guarantee that they will produce either an optimal solution, or even a solution which still looks right on some combinations of terrain and troop deployment doctrine. The challenging aspect of this problem is that there isn't a solution.

There are no approved formulas or mathematically proven relationships between positioning factors and success or failure on a battlefield. There are no concrete formulas which, if specifically followed, will dictate success of a military force on a battlefield. On the other hand, the field consists of a wide variety of literature, general guidelines, and a host of simulations which attempt to predict or replicate the effects of combat based on some lesser degree of resolution than full scale combat in real life. We can, and should, take advantage of one of these simple simulations to refine the weighting criteria for the overall goodness factor used in positioning defensive units.

Simply constructed, this simulation would adjust each of the weighted criteria within a set range and execute a limited force-on-force simulated battle from the ideally selected positions for those weighted criteria, record the results, modify the weights, and repeat. Obviously the implementing programmer or analyst would perform statistical analysis of these factors prior to completing the program in order to preclude wasting real-time CPU cycles varying dependant variables. Pre-runtime experiments should reduce the dependent variables down to a smaller number which, ideally, could be linked to factors such as terrain variability, width of chokepoint, size of force, or some other known factor that would make the initial assessed weighting criteria close to optimum and reduce the run-time variations to minor adjustments or confirmation runs.

2. Comparing Anchor Points

This is the mental simulation piece of RETINA which is so clearly described by Klein in his book and which was demonstrated by the terrain experts in my Dec 2002 experiment. Even with what we believe to be optimal weighting criteria, its important to execute some form of mental simulation (in this case that would require some limited scope force-on-force simulation) from each potential anchor point in order to ensure we've gotten a good estimate of the potential fight and, assuming the anchor point selected is our chosen best place to defend, to use the results of the mental simulation as a tool for defining secondary positioning tasks such as adjusted scout positions, adjusted obstacle locations, and revised reserve positioning. This critical element is conducted extremely quickly in humans prior to assuming that their view of projected reality is viable, and in the authors opinion must be part of any software program that attempts to replicate the effects of human thought.

Using simulation of each anchor point, and as a method of evaluating what we believe to be already optimal solutions should not be seen as a crutch. In pottery terms, we can view mental simulation as the bright light that shines on our clay pots made of heuristics and local optima, exposing weaknesses before we put the pot into the kiln for tempering, allowing us to apply more clay before firing and have a useable pot afterwards.

VI. CONCLUSIONS AND FUTURE WORK

A.   SUMMARY

The goal of this thesis was to produce a deployable system which could replace human operators staffing a simulation exercise; to use a combination of artificially intelligent agents and expert-based heuristics to provide intelligence assessment of terrain and simulated forces on a digital battlefield. That goal has not been achieved. This is due to the scope of effort and research required to bridge the gap between the current work in this field and the total amount required to field such a system. Given the size of this gap, the restated goals for this thesis were to provide a viable approach to modeling human movement tendencies through a digital terrain set, and to provide a conceptual roadmap for an envisioned system implementation based on the author's research and insights.

B.   FUTURE WORK USING FLUIDS TO MODEL HUMAN MOVEMENT

Fluid simulations appear to provide an excellent tool for modeling human movement tendencies through terrain. The avenues of approach and routes created by seeding digital terrain sets with simulated particles and tracking their movement from source to sink are natural in appearance, reflect multiple levels of difficulty in an elegantly simple fashion, and seem to provide a great resource for blind computer algorithms to represent the complex functions of the human eye with respect to seeing terrain as an entity rather than as a set of data points. Future work is indicated in refining this tool and reinforcing the cognitive assumptions upon which it is based, but at a minimum the fluid based approach described previously warrants serious consideration as a technique for modeling human movement.

The flexibility of this approach, combined with its fairly simple mathematical foundation, indicate that this model also could be applied to a large set of problems with varying degrees of evaluation or certainty and provide realistic approximations of those environments for minimal computational cost.   This model provides an excellent approximation of the effects of a real world physical process. The laws of physics which bound gas diffusion are the same laws which bound movement of any object in the real world, namely the principle that objects (in this case humans) seek a predictable path of

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least expended effort (or least resistance, or least action, etc..) as they transition from one state to another.   In my opinion it is because of the global applicability of these laws that we can apply this simple model to very complex environments and achieve similarly valid predicted outcomes.

Three areas of future research are indicated at this time.

1. Cognitive Studies

The author assumes that military units follow the path of least resistance based primarily upon his own experience and training as a military officer. There are relevant published studies of human movement, particularly as vehicles in a traffic pattern, but future cognitive research is indicated to confirm the specific results obtained by a fluid flow simulation as an approach for modeling military movement through terrain. This data could perhaps be extrapolated from digitally recorded maneuvers at one of the Army's training centers such as the National Training Center at Fort Irwin, California, or the Joint Readiness Training Center in Fort Polk, Louisiana.   An interesting study would be to compare the amount of time between receipt of an order, change of direction, change of route, or other event which prompted a departure from the most likely route, and the time (or distance) before the unit's route was again back in a path which could be considered to be a path of least resistance.   My hypothesis is that this time would be surprisingly small for units not in direct contact with an enemy, and that perhaps even while in contact the preferred routes could be identified fairly simply by changing the cost gradient for each terrain cell from a slope-based gradient to a cover-based gradient providing protection from direct fires and observation.   These are fascinating conjectures with great promise for understanding human behavior which deserve future research.

2. Speed Enhancements for Large Data Sets

Current implementation of this model for gas diffusion requires that the model be at a state of equilibrium before the gradient vector field can provide insight or predictable outcomes which match our expectations. The process of identifying these routes and avenues of approach is quick and simple, but the process of producing the gradient vector field for large data sets is cumbersome. Modeling complex terrain environments of adequate size so as to be interesting required a considerable amount of time to produce a state at or near equilibrium. For this model to be worth implementing in a deployable

system, it must be able to produce this vector field in real time, adjusting sources to correlate with current position and projecting forward to the impact of changes at decision points. This problem is surely solvable with additional study and is mentioned here not as a grand research challenge but as acknowledgement of required work that is not completed.

3. Considering the Effects of Friction and Edges

Fluids moving through the real world experience more than simple transference from one cell to the next. Foremost among these effects are those imposed where the fluid comes in contact with walls and edges. These boundary effects alter fluid flow, produce a boundary layer, induce vortices, and are quite significant for some environments. The model described in this thesis takes a deliberate shortcut to modeling these effects with few apparent consequences other than occasional visual incongruities for very small data samples. Further study is indicated to compare the results of this simple model with a more detailed treatment of edge and boundary effects in multiple terrain types and sizes. Will a more complex fluid model provide a gradient which is more realistic than the current pure diffusion field? If so, by how much? And is it worth the computation speed loss to achieve this increase in realism (if such an increase exists)? These questions should all be addressed by future work in this field.

C. PROGRAMMING INTELLIGENT DEPLOYMENT AGENTS

Modeling the recursively fine deployment properties of a real military unit by using an agent-based simulation appears to be an ideal method of accommodating the competing goals of each echelon with the general guidance from higher and the specific demands of the local terrain features. Highest Gradient Hill Climbing (HGHC) agents seek out local optima in exactly the same fashion that a real military unit seeks to find the best defensive position within the boundaries of his assigned sector, mission, and peers. Future work in this area is required in producing the actual model, building a library of deployment templates, and constructing an efficient mental simulation capability.

1. Modeling Deployment Recursively

In this thesis I've described the initial implementation program developed early on in my research as a means of proving the concept. Follow-on work is required to take these concepts and apply them to the full scale terrain model with mature deployment

templates and utilizing the developed terrain values from the RETINA fluid simulation of avenues of approach. Recursive positioning is a must in order to approximate the human methodology of increasingly refined sectors and terrain analysis. Not only will this provide a more realistic application, but it will also free up computation resources. Just as Brigade staffs typically ignore factors such as direct line of sight for each vehicle and individual vehicles seldom consider the missions of adjacent battalions, our program will be able to achieve similar efficiencies by adjusting each agent's goal satisfaction considerations based on his echelon. There is a fair amount of effort required to implement this program, but one can easily envision the high probability of success for such a natural (and human-like) approach to modeling defensive deployment. Similar procedures would apply for offensive movement and actions. Though the parameters of those missions are not discussed in this thesis, the concept of recursively applied agent programming will also succeed for the offensive missions and, one can easily infer, to a host of missions assigned to any organization with well defined goals and responsibilities at each level.

2. Building Useful Deployment Templates

Perhaps the most time consuming work still to be accomplished is production of a useful deployment template library. This is an absolutely critical element of the agent based program because it gives us both the initial formation for the unit before we begin adjusting for terrain as well as the basics of a pattern for the computer vision aspects of RETINA to recognize based on incoming reports. Each type of military unit should be built as a digital template with the doctrinal distances and relationships applied at each echelon. The relationship values can be considered as a means of evaluating each unit's satisfaction of the protection goal (achieved by remaining within the general bounds of the next higher headquarters). In order for our model to provide training benefit, each template must be as described by current military intelligence or threat analysis doctrine and publications.

3. Mental Simulation

Humans conduct mental simulations to project forward the consequences of their decisions as well as anticipated future states of their sensed decision criteria, or cues. Previously I discussed the requirement for a mental simulation to conduct an evaluation

of the weighting criteria for overall goodness of a particular deployment template. This simulation is required, but a similar mental simulation capability is required for evaluating the effects of a force on force battle based on the current defensive array against perhaps the two most likely or most likely/most dangerous enemy attack possibilities. Without these mental simulation capabilities, RETINA is too reliant upon local optima to truly replicate human thoughts. Humans are able to see weaknesses of a locally optimum situation by imagining worst case scenarios and then compensating by adjusting towards the worst case or adjusting the entire defensive position. With only local optima, doctrinal templates, and avenues of approach to guide it RETINA will fail to produce a truly human-like deployment result unless it contains some form of mental simulation to conduct an effectiveness analysis independent of the factors which produced the defensive deployment.

D.   COMPUTER VISION AS TECHNIQUE FOR EVALUATING CHANGES

Using computer vision principles as a means of evaluating inbound enemy situation reports appears to hold great promise. The concepts outlined in this thesis provide initial insights and application principles which, when applied, should give the artificial intelligence program a capability to recognize enemy vehicles as elements in a tactical pattern. Comparing the incoming reports to our pre-combat array of most likely defensive positioning (or to our pre-combat assessment of most likely avenues of approach) as a start point will provide measurable degree of confidence in our assessment as well as suggestions for alternative solutions when our confidence decreases below a reasonable level. This concept holds great promise, and future implementation work is indicated to develop the limits of its potential. Two required components for this work are completion of a behavior library and development of a behavior-inference matrix.

1.   Behavior Library

As discussed in the previous section, one of the shortcomings of the current concept is a lack of movement formations and defensive deployment templates for military units of different sizes and types that could be used for comparison with actual reported vehicles and equipment. In addition to the report of static vehicles and equipment, one capability required here is also the linkage of multiple types of static snapshots into a combined description of behavior. Some of this work may be completed

for some of the classified National Asset systems, but for our purposes a more simple set of heuristics is probably more than adequate to the task.

2. Inferring Intent

This is the most important aspect of future work to be accomplished before RETINA could be employed as a system for real training benefit; developing the matrix which links indicators with intent. It is conceivable that a proof of concept matrix could be developed with minimal expert input to demonstrate simple intent like preparing for a defense, but in order to produce a rigorous action-intention matrix of indicators for certain intentions a more detailed research study is required of both current Army intelligence doctrine as well as detailed interviews with subject matter experts. Ideally, this matrix would include several indicators for each potential intent, each with a degree of certainty (or likelihood) based on factors such as timeliness, proximity, and reliability of the information. Perhaps a thesis in itself, it's this product which allows the analyst to take the assessed results from the previous portions of RETINA and then complete the next step of producing inferred intentions. Once this work has been completed, the trainer can truly claim to have a human-like intelligent agent that can eliminate the requirement for a small portion of the Army's simulation training cost.

APPENDIX A

A.   INTRODUCTION

The source code produced for this thesis is lengthy and exists in several files and Java projects, generally aligned along particular subsets of the thesis.   Terrain sample data was generated by the author for the small test cases and obtained from publicly available DTED Level II files for the National Training Center, Fort Irwin, California. The large data set fluid simulation includes preprocessed concentration and gradient field files stored as ordered text files which are read at run-time by the fluid simulation program.

Nevertheless, these files are publicly available through the MOVES Institute. Please contact Dr. Chris Darken at cjdarken@nps.navy.mil, or the author at rene.burgess@us.army.mil .

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LIST OF REFERENCES

Back, D.N., *Agent-Based Soldier Behavior in Dynamic 3D Virtual Environments,* Masters Thesis, Naval Postgraduate School, Monterey, California, March 2002.

Ballard, D.H. and Brown, C.M., *Computer Vision,* Prentice Hall, 1982.

Beeson, D. *Maupertuis: An Intellectual Biography,* The Voltaire Foundation, 1992.

Benton, J.R., and others, "Tactical Route Planning: New Algorithms for Decomposing the Map," In *International Journal of Artificial Intelligence Tools(1996),* Vol. 5, Nos. 1 & 2 pages 199-218, 1996.

Brogan, D.C. and Johnson, N.L., "Realistic Human Walking Paths," In *Computer Animation and Social Agents (CASA)*, p. 94-101, 2003.

Chorin, A.J., and Marsden, J.E., *A Mathematical Introduction to Fluid Mechanics,* 3d ed., Springer, 2000.

Connolly, C.I., Burns, J.B., and Weiss, R., "Path Planning Using LaPlace's Equation," In *Proceedings of the 1990 IEEE Conference on Robotics and Automation*, pages 2102-2106, May 1990.

Connolly, C.I., "Applications of Harmonic Functions to Robotics," In *Proceedings of the 1992 International Symposium on Intelligent Control.* 26 May 1992.

Darken, C., Class Notes to Artificial Intelligence Course, CS3310, Department of Computer Science, Naval Postgraduate School, Monterey, California, 2002.

Das, S., Grey, R., and Gonsalves, P., "Situation Assessment via Bayesian Belief Networks," *Proceedings of the 5th International Conference on Information Fusion,* Annapolis, Maryland, July 2002.

Das, S., and Lawless, D., "Trustworthy Situation Assessment via Belief Networks," *Proceedings of the 5th International Conference on Information Fusion,* Annapolis, Maryland, July 2002.

Davis, S., "Idle Theory, The Principle of Least Action," [http://ourworld.compuserve.com/homepages/cuius/idle/evolution/ref/leastact.html], September 2003.

de Berg, M., and others, *Computational Geometry: Algorithms and Applications,* 2d ed., Springer, 2000.

Duckham, M. and Kulik, L., "Simplest Paths: Automated route selection for navigation," Accepted for *COSIT'03, Lecture Notes in Computer Science*, Springer-Verlag, 2003.

Ferber, J., *Multi-Agent Systems, An Introduction to Distributed Artificial Intelligence,* Addison-Wesley, 1999.

Forsyth, D.A. and Ponce, J., *Computer Vision: A Modern Approach,* Prentice Hall, 2003.

Forbus, K.D., Mahoney, J.V., and Dill, K., "How Qualitative Spatial Reasoning Can Improve Strategy Game AIs," *AAAI Spring Symposium on AI and Interactive Entertainment*, 2001.

Garrabrants, W.M., "Adaptive Agents for Simulation Object Control," Unpublished manuscript, Nova Southeastern University, 2002.

Gonsalves, P., Rinkus, G., and Ton, N., "A Hybrid Artificial Intelligence Architecture for Battlefield Information Fusion," *2nd International Conference on Information Fusion,* Sunnyvale, CA, 1999.

Headquarters, Department of the Army, Field Manual 34-130, *Intelligence Preparation of the Battlefield,* Washington, DC, 1994.

Headquarters, Department of the Army, Field Manual 71-100, *Division Operations,* Washington, DC, 1996.

Headquarters, Department of the Army, Field Manual 100-5, *Staff Organization and Operations,* Washington, DC, 1997.

Headquarters, Department of the Army, Field Manual 100-60, *Armor- and Mechanized-Based Opposing Force: Organization,* Washington, DC, 1997.

Headquarters, Department of the Army, Field Manual 100-63, *Infantry-Based Opposing Force: Organization,* Washington, DC, 1996.

Henning, C.F., *Designing Realistic Human Behavior Into Multi-Agent Systems,* Masters Thesis, Naval Postgraduate School, Monterey, California, September 2001.

Hill, J.M.D., and others, "Tactical Event Resolution Using Software Agents, Crisp Rules, and A Genetic Algorithm," *Aerospace (MGA) Simulation Symposium,* (Washington, DC, April 16-20). SCS, 15-21.

Hiles, J., Class Notes to Introductory Agents Course, MV4015, MOVES Institute, Naval Postgraduate School, Monterey, California, 2002.

Horn, B.K.P., *Robot Vision,* The MIT Press, 1986.

Horn, G.S., and Baxter, J.W., "An Interactive Planner for Tank Squadron Assaults," [http:// mcs.open.ac.uk/plansig2000/Papers/P8.pdf], September 2003.

Intille, S.S., and Bobick, A.F., "Recognizing Planned, Multiperson Action," In *Computer Vision and Image Understanding,* Vol. 81, pages 414-445, 2001.

Janiszewski, J.J, "The S2 Automated Agent (S2A2): A Training Aid for Commanders and Intelligence Officers," Unpublished masters' thesis, University of Central Florida, 1999.

Kandel, E.R., Schwartz, J.H., and Jessell, T.M., *Essentials of Neural Science and Behavior,* McGraw-Hill, 1995.

Kandel, E.R., Schwartz, J.H., and Jessell, T.M., *Principles of Neural Science,* 4th ed., McGraw-Hill, 2000.

Klein, G., *Sources of Power: How People Make Decisions,* The MIT Press, 2001.

Krogh, B. and Thorpe, C. "Integrated Path Planning and Dynamic Steering Control for Autonomous Vehicles." In *Proceedings of the IEEE Conference on Robotics and Automation,* pages 1664-1669, 1986.

Maupertuis, P.L.M. de. *Oeuvres*. Dresde, 1752.

Orichel, T., *Adaptive Rules In Emergent Logistics (ARIEL): An Agent-Based Analysis Environment to Study Adaptive Route-Finding in Changing Road Networks,* Masters Thesis, Naval Postgraduate School, Monterey, California, June 2003.

O'Rourke, J., *Computational Geometry in C,* 2d ed., Cambridge University Press, 1998.

Pew, R.W. and Mavor, A.S., *Modeling Human and Organizational Behavior: Applicability to Military Simulations*, National Research Council, National Academy Press, 1998 .

Powell, D.R., and others, "Representations to Support Reasoning on Terrain," Los Alamos National Laboratory report, LA-UR-88-3752, 1988.

Richbourg, R., and Olson, W.K., "A Hybrid Expert System that Combines Technologies to Address the Problem of Military Terrain Analysis," In *Expert Systems with Applications,* Vol. 11, No. 2, pages 207-225, 1996.

Reece, D.A., Kraus, M., and Dumanoir, P., "Tactical Movement Planning of Individual Combatants," In *Proceedings of the 9th Conference on Computer Generated Forces and Behavioral Representation,* University of Central Florida, 2000.

Russell, S.J. and Norvig, P., *Artificial Intelligence: A Modern Approach,* Prentice Hall, 1995.

Schlabach, J.L., Hayes, C.C., and Goldberg, D.E., "FOX-GA: A Genetic Algorithm for Generating and Analyzing Battlefield Courses of Action," *Evolutionary Computation, No. 7(1),* Spring, pages 45-68., 1999.

Stam, J., "Interacting With Smoke and Fire in Real Time," *Communications of the ACM,* pages 77-83, July 2000.

Svenson, P., and Sidenbladh, H., "Determining possible avenues of approach using ANTS," In *6th International Conference on Information Fusion,* pages 1110-1117, Cairns, Australia, 2003.

Tyler, J.G., and others. "Knowledge-Based Agents for C2 Decision Support," *Simulation Interoperability Workshop,* Orlando, Florida, 14-16 September 1999.

Wooldridge, M.J., *An Introduction to MultiAgent Systems,* Wiley, 2002.

Yen, J., and Langari, R., *Fuzzy Logic; Intelligence, Control, and Information,* Prentice Hall, 1999.

Zadeh, L., "Fuzzy Sets," *Information and Control,* Vol 8, pages 338-353, 1965.

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