The 10th International Command and Control Research and Technology Symposium

Paper Title:

Terrain Based Prediction to Reduce the Search Area in Response to Insurgent Attacks

Student Paper

Topic: Modeling and Simulation

Dr. Donald E. Brown
Gregory Griffin* (Point of Contact)

University of Virginia
Department of Systems and Information Engineering
P.O. Box 400747
151 Engineer's Way
Charlottesville, VA 22904

434-924-5393
434-982-2972 (Fax)

deb@virginia.edu
gcg5k@virginia.edu

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUN 2005**	2. REPORT TYPE	3. DATES COVERED **00-00-2005 to 00-00-2005**
4. TITLE AND SUBTITLE **Terrain Based Prediction to Reduce the Search Area in Response to Insurgent Attacks**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Virginia,Department of Systems and Information Engineering,PO Box 400747,Cahrlottesville,VA,22904**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES **The original document contains color images.**		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**59**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Terrain Based Prediction to Reduce the Search Area in Response to Insurgent Attacks

Abstract – Insurgents have used mortars to attack their enemies for decades. Iraq is no exception. This paper describes a terrain based technique investigated to predict the most likely routes an insurgent will take after firing his mortar, where along the routes he is likely to be located and which insurgent friendly area he is headed to. Specifically, this prediction method quantifies knowledge of the terrain and knowledge of the enemy's habits to determine his most likely actions. Remote objects represent the quantification of the enemy's habits. These object's influence is calculated using a potential fields method. The *k-best* routes are generated with an A* optimization algorithm using multiple methods to systematically alter the quantified information about the terrain and enemy's habits. Finally, the information is presented to the user through a graphical user interface with the network, routes and the predicted progress of the insurgents along the routes.

1. Introduction - As the United States Armed Forces and their allies continue to operate in Iraq, they regularly come under attack from hostile forces using a number of different means. One of their more popular forms of attack is the use mortars. Defending against mortar attacks is difficult and response to them even more so. Currently, U.S. forces detect the firing of a mortar and receive a grid location for the firing point. However, unless there are aircraft flying over the area that see the muzzle flash, this is the last contact our forces have with the insurgent mortar men.

Mortars allow insurgents to attack from a non-line of sight, covered and concealed position, which provides high pay-off for low risk. Currently, the only signature obtained from a mortar attack is from counter-battery radar or acoustic sensors. These sensors give the location of the firing point. Intelligence reports rarely provide updates regarding where to look for the perpetrators of the attack. In almost all of the attacks, the insurgents get away and our forces are only able to inspect the launch site and recover abandoned equipment.

Initially, the insurgents left the equipment cached at or near the firing point. Soldiers sent to search the site would discover and seize the cached items. After losing a number of weapons systems, the insurgents changed their tactics and began to mount the systems on vehicles. They drove the vehicles to the firing point, fired the mortar and then drove away along previously cleared routes. Our forces changed tactics in response to this adapting threat. Units conduct a detailed analysis of the terrain for firing points and exfiltration routes. When an attack happens, the firing point is identified and troops are guided to the likely escape routes based on an assessment by the operations officer. As time passes after the attack, the operations officer can only guess the current location of the insurgent along his escape route. He moves units to close the insurgents' most likely routes hoping that he moves them ahead of the insurgents' current location. This method works but requires time, some luck and an excellent assessment of the situation in the entire area of operations by the operations officer.

This paper describes a method to use the firing point's reported location to quickly and accurately narrow the search area. The method predicts the *k-best* shortest paths from the firing point to known areas that the insurgent would move to after an attack. This method quantifies the intelligence officer's knowledge of the enemy by generating potential fields that affect the route choice made by the insurgent to return to a friendly neighborhood. This method also incorporates the terrain trafficability for wheeled vehicles to predict progress along likely routes. Progress is a function of time since the attack.

This method incorporates the fields of path planning, path optimization, and discrete choice. Methods discussed in section two are implemented in section three, and followed by a summary.

2. Approaches to Path Prediction –

2.1 Effects of Remote Objects on Path Planning – The affects of the terrain and the enemy's habits must be incorporated in the assessment of routes for the hostile forces. The enemy has habitual ways in which he reacts to the civil climate in the area of operations. The term civil climate describes the overall climate of an area as a function of the people and organizations present in or near them. In this case a positive civil climate is one that is controlled by allied forces and feels influence from government institutions (i.e. police, national guard, allied forces, etc.). Negative climate is one where the influence of government is weak or non-existent and insurgents, militias, and criminals operate freely.

Propagating the effects of a remote object, an object not directly evaluated on the route, is covered by the field of route planning. Much of the research in this area has direct application in the field of obstacle avoidance for autonomous robots. [1], [2], [3] and [4] cover various strategies for implementing obstacle avoidance through potential fields emanating from the robot or the obstacles around them. In efforts to generate these fields they use two different methods: wave propagation and coulombian potential fields.

The wave propagation technique has been used by [1] and [4]. It uses the physical characteristics of waves to describe how the influence of a remote object spreads around obstacles in the environment. It starts at the source of the influence and measures the distance to another point in the environment while flowing around obstacles. The resultant distance is either a Manhattan (L_1) distance or a generalized Manhattan distance depending on whether the space is four-connected or eight-connected. The most effective implementation of wave propagation to this problem is very computationally and memory intensive. It requires starting at the source and expanding each trafficable route one unit at a time. As routes split, new data structures must be created in the memory to track new them. As these new routes become more complex, the storage requirements of the fully enumerated routes increase dramatically.

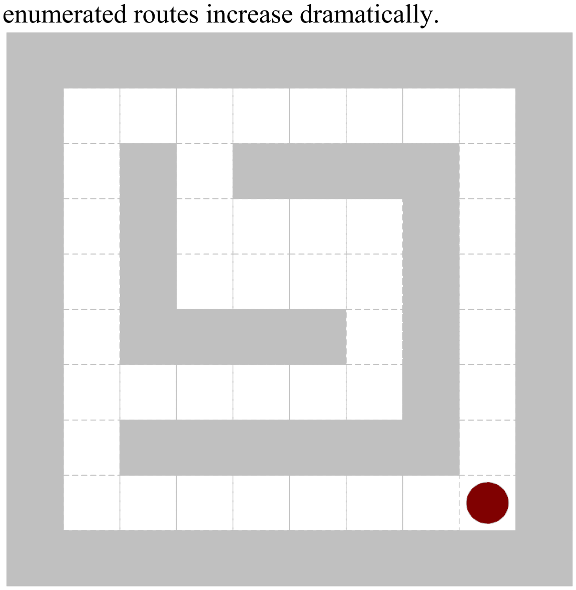


Figure 1. Employing an equal expansion along each path and branching as necessary will enumerate the entire space.

In this application, the terrain has more obstacles than open space. Urban road networks follow the terrain and haphazard urban planning. As the number of routes steadily increases, the iterations through the space slows the wave propagation method down and it becomes an inefficient way to cover the space.

The coulombian potential fields method from electrostatics allows for a much less computationally expensive approach. This method uses the theory behind Coulomb's force. Coulomb's force is the force generated between two point charges.[5]

$$F = k\frac{q_1 q_2}{d_{12}^2}$$

F is the resultant force, k is a constant, q_i is the charge of the particle and d^2 is the squared distance between the two particles.

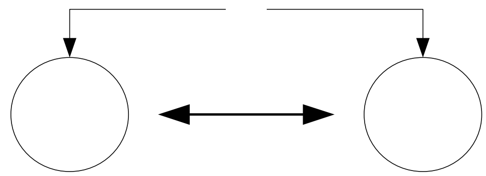


Figure 2. The force that charged particles exert on one another is proportional to size of the charge and the distance between them squared. If the charges have the same sign then it is a positive (repulsive) force. If the charges are opposite, it is a negative (attractive) force.

It is easy to see that if there are multiple charged particles, the resultant force felt by each one with respect to the others is:

$$F = k\sum_{i=2}^{n}\frac{q_1 q_i}{d_{1i}^2}$$

In this application, k is a scaling term used to calibrate the model.

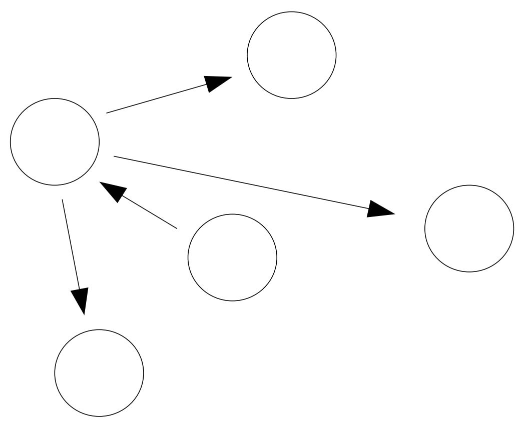


Figure 3. The unresolved forces on charge 1 from the other charges.

Charges represent remote objects that influence the decision of the hostile forces' route selection. For example, Allied checkpoints, bases, police stations, large natural obstacles and choke points (bridges) all received a charge in order ensure they have an effect on the target.

Comparing the results of these two methods, different answers result from two drastically different computational and memory costs. The wave propagation method strictly adheres to terrain, not letting any of the effects of the field penetrate the obstacles (buildings, untrafficable terrain, etc.). The potential field completely ignores the effects of obstacles between the source and the target charge. The disparity in the results forces a re-examination of the desired effect. The following example illustrates the point.

Referring to Figure 4, if the CP is an allied checkpoint and Pt A, Pt B and Pt C all represent possible positions of hostile forces' vehicles, how will the field affect them? Pt A and Pt C are equidistant from the CP using L_2 distance, showing how the potential field solution would calculate the influence. Pt B and Pt C are equidistant from the CP using L_1 distance, showing the wave propagation results. Clearly, Pt C and Pt A do not feel the same influence from the CP. Similarly, Pt B and Pt C do not feel the same influence from the CP either. In the first case Pt A feels more influence from the CP and in the second case Pt C feels more influence.

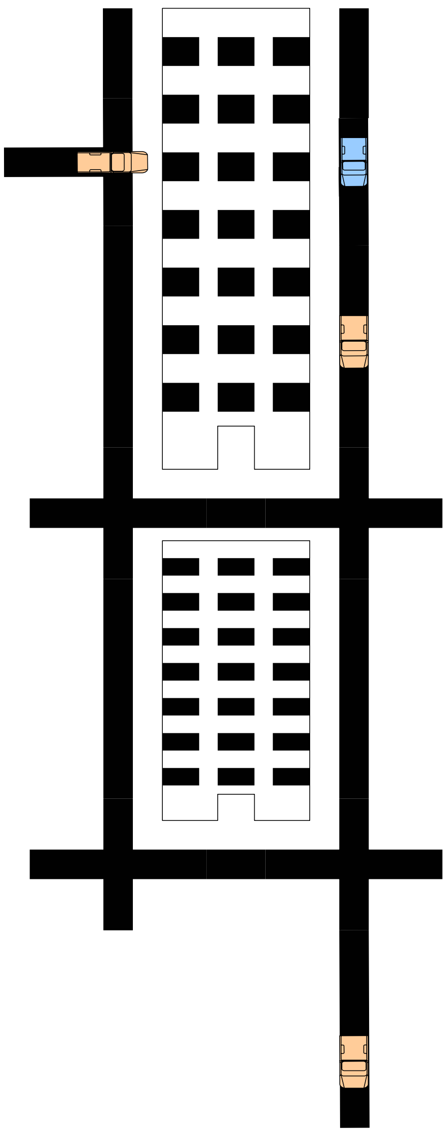


Figure 4. Illustration of the influence of the CP over terrain.

The actual force on the target should be somewhere in between the L_1 and L_2 distances. In order to create that effect, a term based on the amount of interference from non-trafficable terrain can be used to decay a potential fields calculation. This represents the ability of the force, or influence, on an insurgent due to the 'civil climate' or the arrangement of Allied forces in the area to flow through non-trafficable terrain at some degradation. In this case, the aforementioned charged objects (allied checkpoints, bases and the detected firing point) represent positively charged particles while extremist neighborhoods and other areas identified by the intelligence community as friendly to hostile forces are negatively charged particles. Charging the target positively will force it to 'run down hill' to the negatively charged areas and run away from the positively charged areas.

2.2 *k-best* Paths

The hostile forces have shown a propensity for thought out, adaptable planning. This implies that they have conducted thorough reconnaissance of their target area and their escape routes. In developing their routes, they have done some inductive analysis of their movement from the firing point to the goal.

Determining exactly how insurgents weigh their options is difficult. Regardless, they have shown that they do some cost analysis which can be approximated using a shortest path algorithm. Shortest path problems have been around for centuries in many diverse fields. [6] gives an overview of methods for determining optimal performance in network while [7] covers the details of implementation. There are two main methods for finding the shortest path: uninformed search and informed search. Uniformed search explores the space with little information beyond the problem statement. It is forced to methodically search the space, using one of a number of conventions (best first, breadth first, uniform cost, iterative deepening) to determine which nodes to expand first. Informed searches use some knowledge of the search space to more effectively search for the best path. The cost of each route as it progresses through the network has two components. The first denotes the cost of the route taken so far and the second denotes a heuristic cost to get to the end.

$$f(n) = g(n) + h(n)$$

$f(n)$ is the estimated cheapest cost through node n, $g(n)$ is the cost from the start to node n, and $h(n)$ is the estimated heuristic cost from node n to the goal. This heuristic must be *admissible*. An admissible heuristic never overestimates the cost to get to the goal [7]. Given that informed searches utilize more of the available information, they take less time and memory than uninformed searches making it a better method for this implementation. The method used here is known as A*.[7] It is a best-first search method with a heuristic to pull it to the goal state. This algorithm is originally developed in [8] in 1967.

Adjusting the attributes used to calculate the weights of the arcs and nodes allows you to adjust the outcome of the optimization. Determining which attributes to include and how they are weighted can portray different characteristics of the hostile forces. Having this flexibility to adjust the optimization will allow the program to adjust as the insurgents adjust their tactics.

Knowing that our model may not be exact with respect to how hostile forces view the dangers and trafficability of the arcs and that people do not always make optimal choices, finding the *k-best* routes by adjusting the network will improve the likelihood of including the route the insurgents chose. Removing a node from the unconstrained best route alters the route enough to induce variability to find *k* routes.

Three different methods for selecting which node to choose were considered. First, a uniformly random process over all the nodes in the optimal path was used. The network was re-optimized with the random node removed. This yielded a baseline with which to compare our other methods. Next, a node was selected based on its threat value. Taking them out of the optimal unconstrained route one by one and re-optimizing, *k-best* routes were found again. The final method looked for the critical nodes in the path that, if changed, would drastically alter the entire path. These critical nodes or chokepoints could be directed manually or selected automatically. This set of routes gives the widest possible spread of routes and could be used in situations where our forces could attempt to shape the battlefield by changing their stance in the area.

These last two methods can be viewed as using increasing amounts of knowledge of the battlefield and the enemy. When removing the nodes with the highest threat value, it is assumed that the most important aspect of a route is the avoidance of Allied forces. Going one step further, we can use this ordered list of nodes to find a threshold that we can institute in the route generation process that prevents the addition of a node that exceeds a certain level of threat. Using the critical nodes approach, even more information of the battlefield is used. It identifies the nodes, that when denied, force the insurgent to make other choices. This shaping of the battlefield can allow the user to analyze the best areas to allocate his forces. When combining the ability to adjust the optimization algorithm and the different methods for generating the k-best routes, any number of characteristics of the enemy's decision making process can be simulated.

2.3 Assessing the Probabilities for the Routes.

Determining the probabilities that the insurgents will use one of the optimized routes comes from the field of discrete choice. [9] covers the early foundation of discrete choice. A common and powerful way to assess the probabilities of individual choices from a set is to use the Multinomial Logit Choice Model. Logit choice models classify data into one of a set of choices. These models produce a probability that a particular choice is made given the characteristics of the candidate data point. Logit choice states that choices have a utility relative to one another. This utility has two components: a deterministic component, *v*, and a stochastic component, *e*. [10]

$$u_i = v_i + e_i$$

Assuming that the error term has a Weibull distribution and that the expected value of the stochastic component is zero we can derive the probability of a choice. In particular the probability of any one of the choices being selected as a function of the exponential of the utility is seen below.

$$p_i = \frac{\exp(v_i)}{\sum_k \exp(v_k)}$$

Where p_i is the probability of event *i* happening and v_i is the deterministic component of the utility of the choice. Using the optimized route scores as the utility allows the assessment of the probability that the insurgents will choose one route relative to another route.

A property of the Logit Choice Model is the Independence of Irrelevant Alternatives (IIA). This property maintains the ratios between alternatives no matter how many alternatives are added or taken away. While this property does have intuitive problems from a computational standpoint it can help. As each alternative is added, it reduces the probability of each of the choices equally. This allows for routes to be added or taken away from the set without disrupting the ratios between the remaining routes.[10]

3. Implementation

3.1 Initial Data Requirements

This approach requires three matrices of data about the network that represent the trafficable terrain, one matrix of influential points data and the firing point to make its prediction. The three network data matrices quantify the terrain into a network of arcs and nodes. One matrix contains the node locations. Another contains the information on the arcs consisting of the nodes that the arc connects, the length of the arcs and their assessed trafficability. Finally, the last network matrix relates the nodes to the arcs. The influential points matrix has all the locations that have a charge on them and the magnitude and sign of the charge. This is the quantification of the intelligence information that the Intelligence Officer has gathered on enemy and friendly locations.

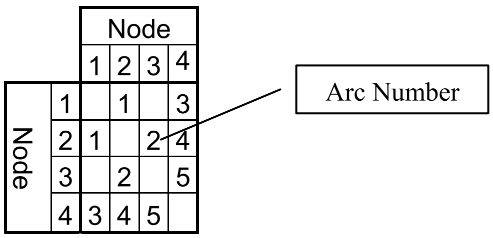


Figure 5. Illustration of the Node to Arc Matrix used to quantify the terrain information.

3.2 The heuristic

Using this initial data, a heuristic for the informed search needs to be developed. The heuristic must not overestimate the cost of getting to the goal. One such heuristic is the road distance from the goal to the start point. This distance was determined using an uninformed search method based on Dijkstra's Algorithm and is detailed in [7]. This method enumerates the entire space, finding the distance from each node to the goal node. This method is guaranteed optimal if all the arcs are positively weighted. This heuristic meets the requirement not to overestimate the cost to the goal from each node.

3.3 Weighing the arcs

Quantifying the intelligence information from the influential points matrix requires using the potential fields method for assessing the threat at each point in the network. Since the decision to go down an arc is made at the node, assessing the field strength at the nodes and weighting the nodes with this value accurately represents that decision.

The calculation of field strength requires not only the charges and the distances between them, but also the magnitude of the decay of the field as it passes through obstacles. Calculating the amount of obstruction requires finding the portion of the straight line (L_2) distance between the influential point and the target. Measuring the portion of the line that crossed non-trafficable terrain yields the amount of obstruction between the target and the point of influence.

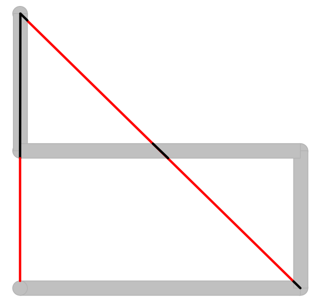


Figure 6. The red portions of the line are elements that contribute to the obstruction value.

Combining the field value and the obstruction value requires scaling to appropriately weigh the quantities.

The arc information matrix has the arc length and the arc's trafficability rating. The trafficability rating is determined by the physical characteristics of the arc (road). The width, grade, surface condition and congestion are all considered in this factor. The factor represents an overall effect on a vehicle's maximum speed. The vehicle's maximum speed is multiplied by this factor to determine the actual speed that the vehicle can attain on the terrain. The trafficability rating here represents the average trafficability of an arc.

3.4 Finding the shortest path and determine probabilities.

The A* algorithm is used to find the shortest path from the firing point to the goal across a network of weighted arcs and nodes. The arcs are weighted with trafficability while the nodes are weighted with the heuristic function (road distance to the goal) and the threat field. With these attributes an unconstrained optimization was calculated and the path with its score was saved. Then, with selected nodes removed from the network, the optimization was re-calculated, saving the shortest paths and their scores to get the *k-best* routes to the goal.

Using the shortest path score as the utility of each of the *k-best* paths, the Logit Choice Model was applied. Logit Choice assumes the best value is the highest value. In this situation the opposite is true. To overcome this, a transformation of the score that maintained the magnitudes and dispersion of the scores was needed. Calculating the probability of the routes being used returns an easily understandable answer in a familiar form.

3.5 Tracking the progress.

Finally, to make this usable to the operations officer, a graphical user interface is created. It shows where the target is along the routes as a function of time. The program draws the routes on the map and then tracks the targets with a time distance calculation, using the vehicle speed from the maximum speed multiplied by the trafficability calculation. The effect of the terrain on a vehicle's ability to travel across it requires the incorporation of all the physical attributes of the terrain. Attributes include the surface material, width of the road way, slope, and weather effects. In order to get the best predictability, we incorporated the Army standard for simulation that governs the movement of vehicles in simulations.[11] This improves the accuracy of the predicted speed that the insurgents are traveling over the route.

Once this speed has been used to calculate the position of the insurgent, his progress is plotted on the different routes in 5 second increments. This shows the user where to vector troops to intercept them on their way to their base.

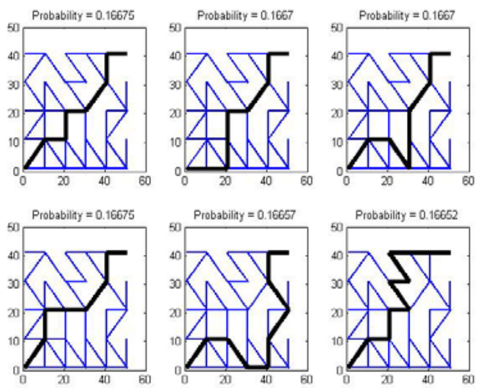


Figure 7. Sample output of network with the six (k) best paths outlined and their associated relative probabilities.

4. Summary

The current method of responding to insurgent attacks incorporates many of the methods described here. There is a detailed analysis of the area of operations around likely mortar targets. Firing points and routes of egress are identified and then monitored. When an attack happens, the operations officer has to look at the map, identify the firing point, the locations of friendly units and the routes from that firing point to the insurgent friendly areas. All this is done manually and requires the operations officer to analyze the situation and control the response simultaneously. With this tool he can use it to process the current situation based on the previous analysis done by the staff, so he can focus on controlling the situation as it unfolds. No information will be inadvertently left out and none of it will be out of date. With the operations officer to control the response to the attack, he can focus on getting the right units to the right locations in time to be effective. In this fast paced fluid environment, every second counts.

Use of this method is not restricted to counter mortar operations. This technique can be applied to any situation in which contact with the enemy is lost but the enemy's goal locations are known with some certainty.

This method of automating counter mortar battle drills has some distinct advantages. It is fast, accurate and can be utilized by every unit in the theater. Running the optimization takes less than two seconds to determine the *k-best* routes and plot them from the firing point to the goal. It never forgets to think of a factor in the movement or which path the insurgent can make better time on. It also adapts as the posture of forces changes. This method relies on information and is not reliant on the strength of the officers and NCOs to ensure that it is successful.

With all the advantages that it can provide, it does have some very restrictive drawbacks. It assumes that the enemy is road or trail bound, or at the very least road/trail centric in his movements. This is a reasonable and realistic assumption in urban settings but becomes less so as the terrain becomes more trafficable in rural environments. The construction of the network also relies on having a perfect picture of the underlying terrain. If there are unknown trails or paths through the terrain then the network no longer accurately represents the terrain and the paths are not truly optimal. The cost function may not have all of the factors related to the decision process of the insurgent. Without being able to analyze the insurgents thought process, we have to approximate. Knowing how an insurgent successfully escaped is difficult to determine past the initial movement from the firing point.

This area of research still has much room for refinement. Incorporating ways to automate the generation of the network and the terrain matrices that support it would drastically reduce the time it takes to initialize the program once it is in an area of operations. While generating this network, maintaining the network as an overlay on the map itself would increase the soldier's situational awareness and ability control the response.

Changing the method for calculating the distance between the target and the charged point of influence for the potential field calculation will yield a different result. Evaluating the strength of the field along the entire arc to find its maximum and using that as the threat field strength will produce another scheme for the insurgents' decision making. Also, using different values to distinguish the different types of the non-trafficable terrain for the decay of the field or using different attributes for the optimization will produce a different k-best set of solutions. Also, setting thresholds to bound the upper and/or lower limits on the optimization would show different characteristics of decision making in the path planning process.

A major change would be the incorporation of this program directly into the battle command system. The program would get automatic updates on the status of friendly forces and the reports of the firing point, decreasing the time it takes to calculate the route even more. This would ensure the program optimizes with the most current data without having to manually update when the friendly forces change their disposition.

Lastly, expanding this methodology to a non-road/trail scenario where the enemy is not necessarily vehicle mounted increases it potential for application across the entire theater. Anytime we have a reasonable read as to the starting point and goal of an enemy unit and good terrain analysis we could apply this method to a continuous, non-network based method that would incorporate the terrain and disposition of forces to predict the location of the enemy along possible routes of egress.

Works Cited

[1] Brown, D.E. and Nougues, P.O., We know where you are going: tracking objects in terrain, *IMA Journal of Mathematics Applied in Business and Industry*, Vol. 8, 1997, 39-58.

[2] Chen, Danny Z., Szczerba, Robert J. and Xu Bin, A New Algorithm and Simulation for Computing Optimal Paths in a Dynamic and Weighted 2-D Environment, *2000 IEEE International Conference on Systems, Man, and Cybernetics*, Vol. 1, Oct 2000, 313-318.

[3] Hwang, Y.K. and Ahuja N., A Potential Fields Approach to Path Planning. *IEEE Transactions on Robotics and Automation*, Vol. 8, No. 1, Feb 1992, 23-32.

[4] Poty, A., Melchoir, P. and Oustaloup, A., Dynamic Path Planning for Mobile Robots Using Fractional Potential Field, *First International Symposium on Control, Communications and Signal Processing, 2004*, 557-561.

[5] Grant, I.S. and Phillips, W.R., The Elements of Physics, Oxford University Press, New York, 2001.

[6] Bertsekas, Dimitri P., Network Optimization: Continuous and Discrete Models, Athena Scientific, Belmont, MA, 1998.

[7] Norvig, Peter and Russell, Stuart, Artificial Intelligence: a Modern Approach, Prentice Hall, Saddle River, New Jersey, 2004.

[8] Hart, Peter E., Nilsson, Nils J., and Raphael, Betram, A Formal Basis for the Heuristic Determination of Minimum Cost Paths, *IEEE Transactions on Systems Science and Cybernetics,* Vol. SSC-4, Number 2, July 1968, 100-107.

[9] Bierlaire, Michel, Discrete Choice Models, found at http://rosowww.epfl.ch/mbi/papers/discretechoice/paper.html

[10] Carroll, J. Douglas, Green, Paul E. and Lattin, James M., Analyzing Multivariate Data, Thomson Learning Inc., Pacific Grove, CA, 2003.

[11] The Army Standards Repository System (ASTAR), found at http://www.msrr.army.mil/astars/

Terrain Based Path Prediction

MAJ Gregory Griffin

June 14, 2005

Outline

- Introduction
- Motivation
- Approach
- Validation
- Contributions
- Questions

Introduction

- The Path Prediction Tool (PPT) was designed to aid deployed military units' responding to a mortar attack and Homeland Security officials responding to a shoulder-fired missile on a commercial airliner.
- Uses the products of the Intelligence Preparation of the Battlefield (IPB) process to build a weighted arc-node network, then finds the *k-best* paths through it.
- Displays those paths on a map.

Motivation (1 of 2)

- Two current threats to Americans have motivated this research.
- The threat of mortar attacks against Allied forces in Iraq and Afghanistan.
- The threat of a surface-to-air missile fired at commercial aircraft landing and taking off from airports
- Both attacks have at least two things in common.
  - A quickly identifiable firing point.
  - No other reports on the attacker after the initial firing point location.

Motivation (2 of 2)

- Prevention of either of these types of attacks would be the best solution, however that is extremely difficult.
- Finding a better response is the next best solution.
- The enemy tactics and the characteristics and trafficability of the terrain can all be quantified to reflect how the enemy plans their paths of escape.
- Assemble all the information together and generate a path planning tool to help Allied forces in Iraq and Homeland Security agencies domestically to predict what paths the attacker will take back to his hideout after the attack.

Research Goal

- Develop a tool that assembles and quantifies information on enemy tactics and the terrain and generates the likely paths the attackers would use to escape from the firing point to their hideout. This tool will also display the paths on a map and maintain a current estimated location along those paths as a function of time.

Approach (1 of 6) -

- Convert the terrain and points of influence into a weighted node-arc network.
- Optimize the network to find the shortest path through it.
- Systematically alter the network to generate the *k-best* paths.
- Determine the probability that a particular path will be chosen.

Approach (2 of 6) –

- The PPT uses quantification of the geography and tactics of the enemy.
- The quantification places the data into three matrices for terrain, one matrix for points of influence, and the firing point.
- The three terrain matrices quantify the roads, intersections, and road conditions.
- The points of influence consist of the node that it is nearest to and the magnitude of the charge which reflects the amount of influence it is expected to have.
- The firing point is input as it is available.

Approach (3 of 6) –

- For a shortest path algorithm to work it needs the network to have weights on the arcs and nodes.
- The tool uses three factors to weight the arcs and nodes in the network.
  - Threat Score – Decayed Artificial Electric Field
  - Trafficability or Terrain Effects - NRMM
  - Road Distance – Dykstra's Algorithm

Approach (4 of 6) –

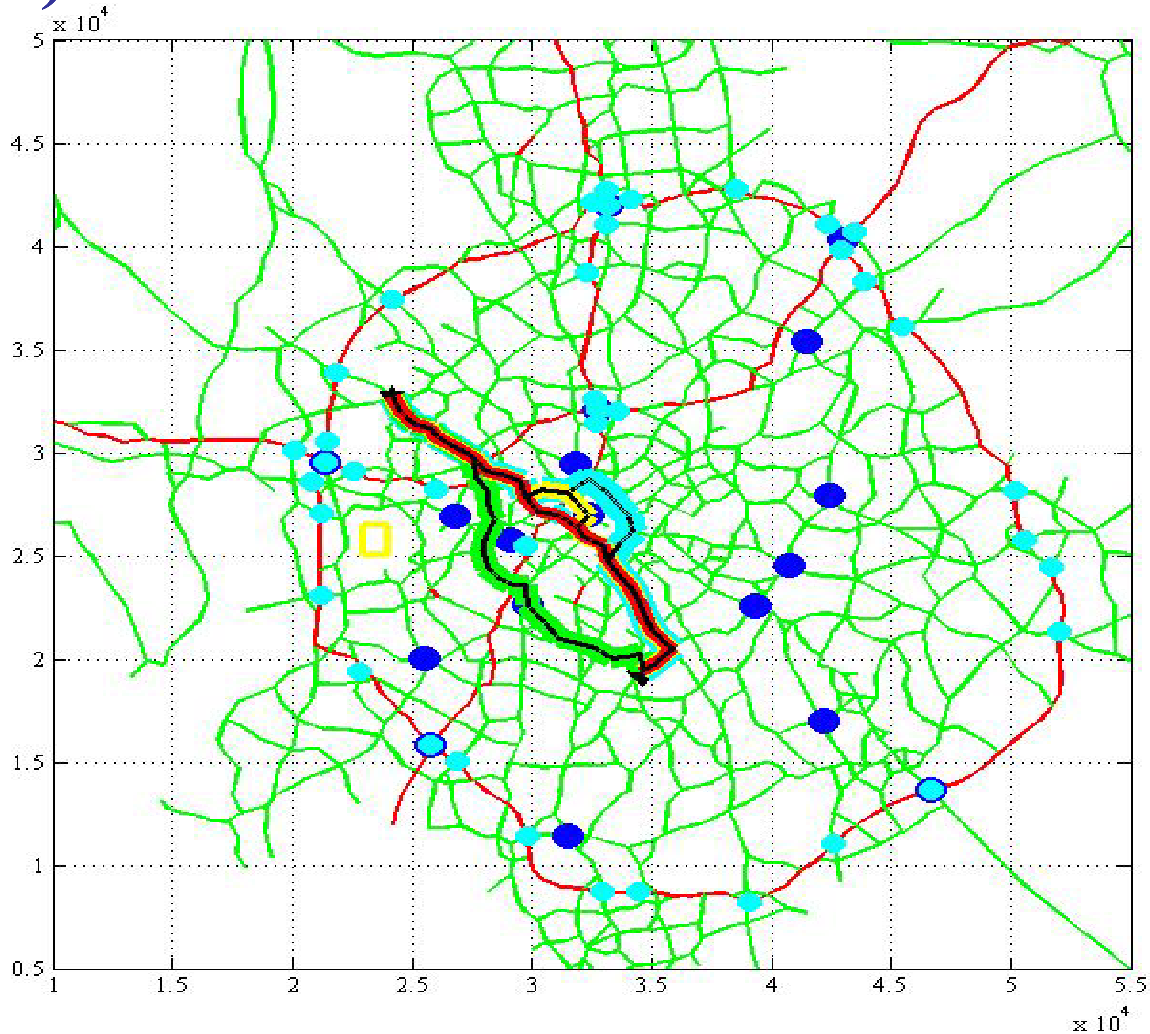
- All available data prior to an attack is collected.
- The tool pre-computes the threat surface and awaits the attack to get the firing point.
- Longest portions to calculate are the transforming of the map into a binary matrix that the obstruction value calculation can use and the threat score as it evaluates all the obstruction values.

Approach (5 of 6) –

- Once the firing point is determined an informed search algorithm (A*) is used to determine the shortest path.
- In order to get the *k-best* paths, we remove nodes from the path systematically based on their threat score.
- Determine the probability of the path being used through discrete choice.

Approach (6 of 6) -

- The result displayed to the user as a map with the network, influential points and potential goal locations on it.
- Additionally the *k-best* paths are depicted in different colors depending in the probability that the enemy would use it.



Validation (1 of 12) –

How to validate without ground truth

- In order to validate, need real data or simulated data.
- Real data is classified, simulation would be rather circular.
- Developed a series of experiments set in two different scenarios and got an expert in the area to predict the paths of the insurgents or terrorists based on their personal, professional opinion.
- One scenario located at a domestic airport and the other in a town in the Southwest Asia.
- The experiments had the subject assume the role of the enemy. The subject was given the map with influential points on it, the firing point and goal locations. They were asked plot paths for the enemy to escape.

Validation (2 of 12) –
Design of the experiment

- Each scenario had three experiments in it.
  1. Plot the single shortest, road distance path from the firing point to the goal location. Ignore all influential points in the terrain.
  2. Plot the four best paths to one goal location, taking into accounts all the influential points.
  3. Plot the four best paths to any of three goal locations, taking into account all the influential points.
- Not all the subjects were experts in the areas of interest. There was a second non-expert group that provided a lower bound on the performance, whereas the expert group provided an upper bound on the expected performance.

Validation (3 of 12) – Metrics

- The metrics can be grouped to reflect which factors of the enemy's decision making process they measure.
- Threat: Overall path threat score, and maximum, minimum and average threat values for the nodes of the path.
- Shortest amount of time: Path time, Number of path segments, path length.
- Metrics for determining the similarity with the expert:
  - Predicted Path Deviance (PPD)
  - Number and percent of nodes that were the same

Validation (4 of 12) -
Predicted Path Deviance

- PPD is a measure of the area between the two paths and divided by the expert path length.
- This reflects the fact that a parallel path that is near the optimal will score better than a shorter or longer path that does not closely follow the optimal path.

$$\frac{\sum Area_{sp}}{L_p}$$

Validation (5 of 12) – Charlotte Airport results

- For this scenario, the expert was a subject who had conducted a study of the Charlotte airport for vulnerabilities to surface-to-air missile attack.
- In Experiment 1, the subjects, in general, did not find the optimal path. All of the metrics showed that humans, even without competing constraints, have trouble finding optimal solutions.
- In Experiment 2, the path prediction tool was tuned to the characteristics of the expert/enemy. By adjusting the weights on the three components of the arc and node values, the tool found results that reflected the decisions predicted by the expert.
- The tuned tool was able to consistently outperform the non-expert subjects.

Validation (6 of 12) –
Charlotte Airport results

- A sample of the results from Experiment 2.

	Expert	Computer	*Diff*	Subjects	*Diff*
Number of Segments	28	24	4	32	4
% Same Segments			39.29%		57.22%
Length (m)	20464	19539	925	24016	3552
Max. Threat	0.5428	0.5480	0.0051	0.5588	0.0739
Min Threat	0.1608	0.1164	0.0444	0.1608	0.0000
Average Threat	0.3295	0.3345	0.0050	0.3414	0.0241
Travel Time (sec)	12324	10157	2167	14584	2260
Threat Score	4.2038	3.4431	0.7607	5.1328	0.9821
PPD			89.338171		1319.9039

Validation (7 of 12) –
Charlotte Airport results

- In Experiment 3, the same weights on the factors in the optimization were maintained to plan the paths.
- Sample results from Experiment 3.

	Expert	Computer	*Diff*	Subjects	*Diff*
Number of Segments	44	44	0	50	6
% Same Segments			52.27%		39.74%
Length (m)	35350	37149	1799	38983	3848
Max. Threat	0.6376	0.6716	0.0339	0.6460	0.0084
Min Threat	0.2278	0.2278	0.0000	0.2222	0.0056
Average Threat	0.3595	0.3634	0.0039	0.3687	0.0156
Travel Time (sec)	22603	22603	0	24706	2103
Threat Score	9.4312	9.6221	0.1909	11.9361	2.5543
PPD			53.832987		1118.1181

Validation (8 of 12) –

Southwest Asia results

- For this scenario, the experts consisted of four Operation Iraqi Freedom Veterans who had experience with insurgent mortar attacks.
- In Experiment 1, none of the subjects faired any better than the subjects in the Charlotte scenario. This time only one subject found the optimized shortest road distance.
- In Experiment 2, the same factor weights were used for the tool's optimization. The tool is designed to be adjusted to fit the tactics of the enemy in each area of operations. The tool was not recalibrated because of the sparseness of the data.
- Regardless, the tool performed well against the non-expert subjects.

Validation (9 of 12) –
Southwest Asia results

- The experts' responses are averaged for the path metrics. When assessed against the non-experts, each path is compared one-to-one and then averaged.
- In Experiment 2, the tool outperformed the non-expert subjects three out of four times in all areas.

	Expert	Computer	*Diff*	Subjects	*Diff*
Number of Segments	92.25	77	15	88	5
% Same Segments			50.91%		44.66%
Length (m)	32699	29892	2807	30216	2519
Max. Threat	0.8392	0.8236	0.0156	0.8313	0.0108
Min Threat	0.0000	0.0000	0.0000	0.0000	0.0000
Average Threat	0.5732	0.5604	0.0127	0.5812	0.0111
Travel Time (sec)	13492	9455	4037	11719	1987
Threat Score	1.2193	0.9809	0.2384	1.1416	0.0822
PPD			45308.311		56898.5954

Validation (10 of 12) –
Southwest Asia results

- In Experiment 3, the tool outperformed the non-expert subjects three out of four times in all areas.

	Expert	Computer	*Diff*	Subjects	*Diff*
Number of Segments	62.5	45	18	60	13
% Same Segments			5.71%		25.29%
Length (m)	25357	22292	3065	23081	6157
Max. Threat	1	0.8816	0	0.8280	0.0994
Min Threat	0	0.5434	0	0.0310	0.2536
Average Threat	1	0.6928	0	0.6657	0.0264
Travel Time (sec)	6787	0	6787	5673	4316
Threat Score	0	0.1061	0	0.4489	0.2856
PPD			98870.173		99097.2254

Validation (11 of 12) – Significance

- T-tests were conducted on the results from both scenarios.
- Tested two hypotheses:
  - Were the tool results actually different from the non-expert subjects.
  - Were the tool results the same as the expert subjects.
- Used four metrics (PPD, Average Threat, Threat Score and Travel Time) to determine the similarity of the PPT results and the non-experts results.
- Used three metrics (Average Threat, Threat Score and Travel Time) to determine the similarity of the PPT results and the experts results.

Validation (12 of 12) – Significance

- Hypothesis 1, are the PPT results different from the non-expert group.
  - The majority of the tests for the metrics concluded that they were different at a significance level of 0.1.
  - The results were not unanimous across all the metrics.
- Hypothesis 2, are the PPT results the same as the expert group.
  - The majority of the tests for the metrics concluded that they were the same at a significance level of 0.1.
  - The results were not unanimous across all the metrics.
- A good result for such a small data set. Expect results will get better with more testing.

Contributions

- Developed a new approach to path planning with an expanded definition of terrain.
- Demonstrated application to problems of security and military operations.

Future Work

- Future work can extend this in two ways:
  - Calculate the threat for each arc at the point in the arc where the field is the strongest.
  - Move this off of the network and into a continuous realm. An interim is to have different networks for different modes of travel to include dismounted.

Conclusion

- Questions
  &
  Comments

Backup Slides

Related Research (1 of 8) –
Military mission planning and the terrain

- Mission Planning in the Military
  - Always account for the terrain and the enemy
- Assessment of the terrain: OAKOC
  - Obstacles
  - Avenues of Approach
  - Key Terrain
  - Observation and Fields of Fire
  - Cover and Concealment
- Accounting for these factors, military forces incorporate the effects of terrain on the planning process.

Related Research (2 of 8) –

Military mission planning and the enemy

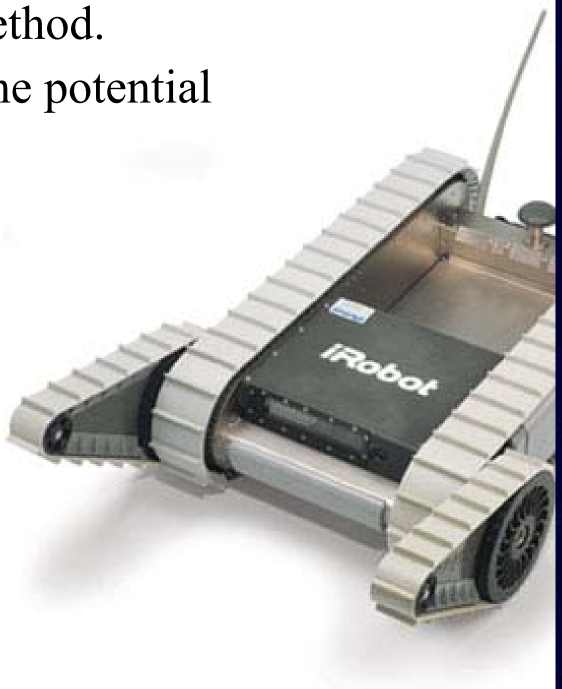
- Intelligence Preparation of the Battlefield (IPB)
- The mission planner looks at the enemy's past actions and tactics to anticipate what they are going to in the upcoming mission.
- The intelligence officer produces a template, adjusted for terrain, that quantifies his best guess as to the location or actions of the enemy on this particular mission.
- These guesses are grouped together into possible Coarse of Action (COAs) for the enemy.
- The terrain assessment through OAKOC and the enemy assessment through IPB can be applied to the current threats that we have to our forces.
- This research proposes to use the products of these existing processes to automate the COA generation and weighting of the likely paths the insurgent or terrorist would use to escape after an attack.

Related Research (3 of 8) –
The planning priorities of the enemy

- In order to develop an accurate tool, something needs to be assumed about the insurgent and terrorists minds and what they consider important in the path planning.
- Looking at current behavior in the insurgent a couple of observations can be made.
  - The insurgent is smart and adaptive
  - He will avoid allied forces
  - He will take the path that takes the least amount of time to get from the firing point to his hideout.
  - He will always take paths that allow him to maintain his flexibility.

Related Research (4 of 8) –
Path planning

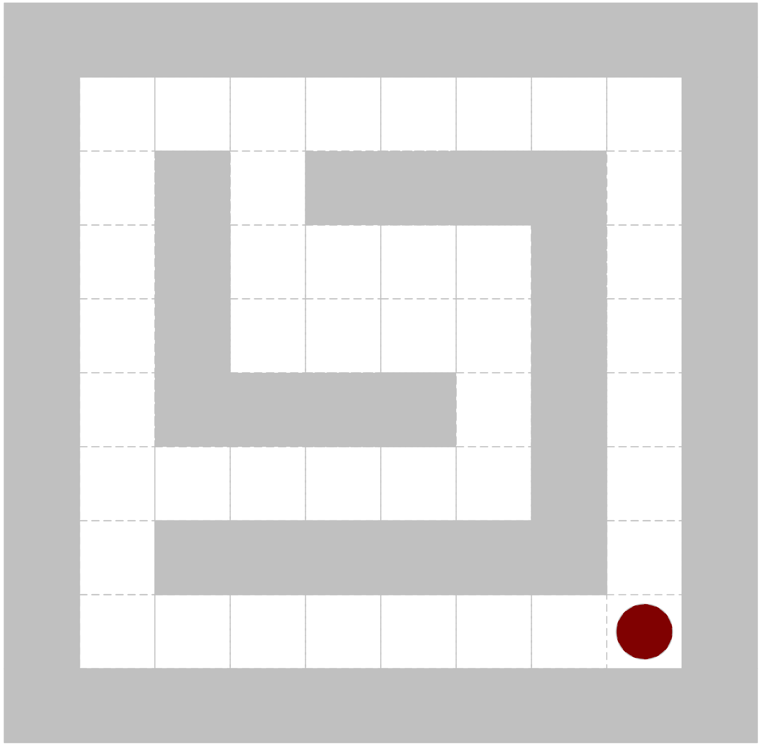
- Automated path planning explored by many fields and extensively by robotics and computer game programmers.
- Most use a potential fields method.
- Two main ways to generate the potential fields:
  - Wave Front Propagation
  - Artificial Electric Field



Related Research (5 of 8) –

Wave Front Propagation

- Starts from one point and the expands equally outward, counting the units of distance as it goes.
- Each branch of trafficable terrain generates its own data structure and all the paths to that point needs to be stored.
- Requires extensive amounts of memory and computer time in order to compute.



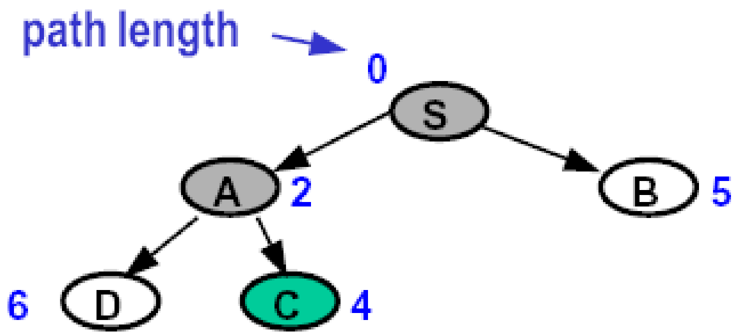
Related Research (6 of 8) –
Artificial Electric Fields

- Based on Coulomb's Law
- Force is a function of charges and squared distance between them
- Radiates equally in all directions regardless of the underlying surface

$$F = k\frac{q_1 q_2}{d_{12}^2}$$

Related Research (7 of 8) –
Network Optimization

- Many problems can be converted into network shortest path problems.
- Search methods can be broken into two groups: Uniformed and Informed.
- Uniformed uses only information from problem statement.
- Informed uses as much information as you can quantify for it. This additional information shows up as the heuristic value.



$$f(n) = g(n) + h(n)$$

h(n)

Related Research (8 of 8) –
Discrete Choice Models

- Evaluates the relative probabilities of choices from a set.
- Uses a utility score to compare the choices to one another.
- Logit choice's significant advantage over Probit is the closed form nature of the answer.

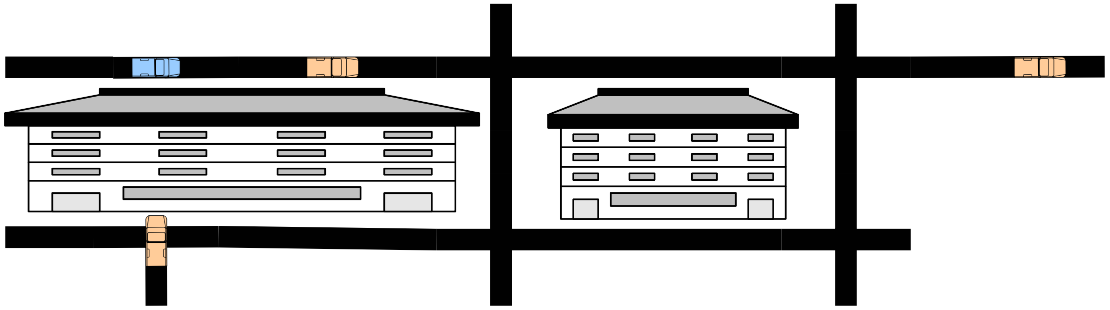
$$u_i = v_i + \varepsilon_i$$

$$p_i = \frac{\exp(v_i)}{\sum_{k=1}^{n} \exp(v_k)}$$

DC

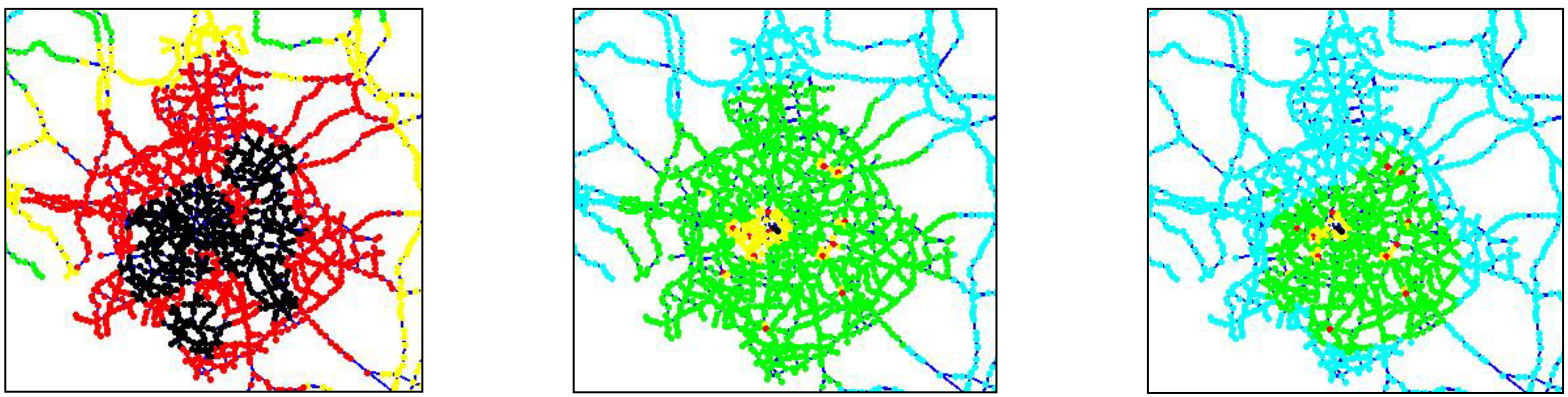
Proposed Approach (3 of 12) –
Choosing the Potential Field generation method

- The threat score uses the potential fields method to calculate the level of threat the insurgent or terrorist feels at each node as he is making his path decision.
- Which method to use? The two different methods yield two very different results.
- Wave Propagation strictly follows terrain.
- Artificial Electric Field completely ignores terrain.



Proposed Approach (4 of 12) –
Choosing the Potential Field generation method

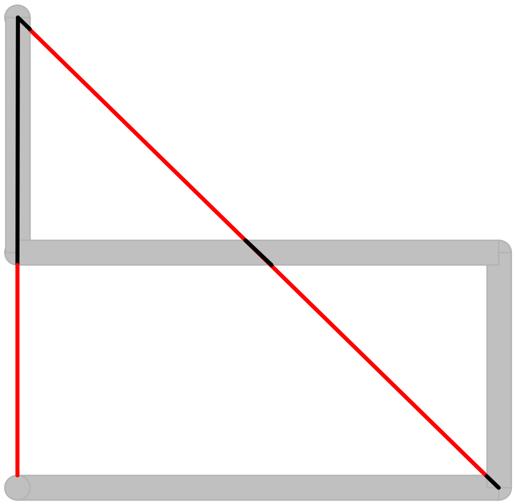
- Solution: Use a computationally cheap artificial electric field that has a decay term based on the amount of un-trafficable terrain between the source and the target.

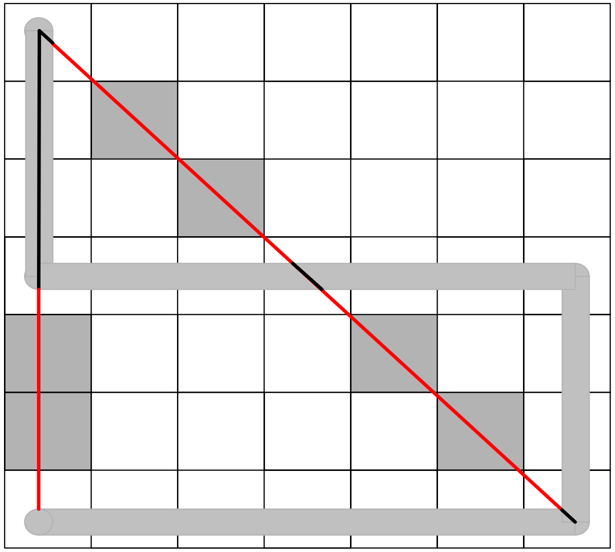


Graph

Proposed Approach (5 of 12) –
Choosing the obstacle value calculation method

- Calculation of the obstacle value was done via two different methods.
- Small network: straight line calculation of obstruction.
- Large network: area calculation of obstruction.





Graph

Proposed Approach (6 of 12) –
Calibration of the Threat Score

- There are three different factors that can be adjusted to calibrate the threat score to accurately model the effect that was sought.
  - Obstacle value
  - Distance scale
  - Zero-distance value
- When the three values were properly scaled (all in meters) or weighed, the nodes at the point of influence or its immediate unobstructed neighbors were separated from the rest of the nodes.

Proposed Approach (7 of 12) –
Trafficability calculation

- Trafficability of the terrain is quantified as a maximum speed that a class of vehicle can attain on an arc.
- These speeds were calculated from the NATO Reference Mobility Model which standardizes all NATO military ground simulations.
- The trafficability enters the optimization in two ways: determining which route is more trafficable (higher score is better) and then determining the amount of time it will take to traverse an arc.

Proposed Approach (8 of 12) –
Road Distance Calculation

- The heuristic that the informed search algorithm needs to optimize the shortest path is a shortest driving distance measure.
- Used Dykstra's algorithm with an added component for remembering its path.
- Guaranteed optimal which meets the admissible heuristic requirement of never overestimating the distance to go.

Admissible Heuristic

- The heuristic for an informed search is the measure from a node in the network to the goal.
- Can be anything (number of moves, Euclidean distance, etc.)
- For a heuristic to be admissible it cannot overestimate the measure to the goal.
- Prevents the heuristic from pulling the search in the wrong direction and guarantees optimality.

Back

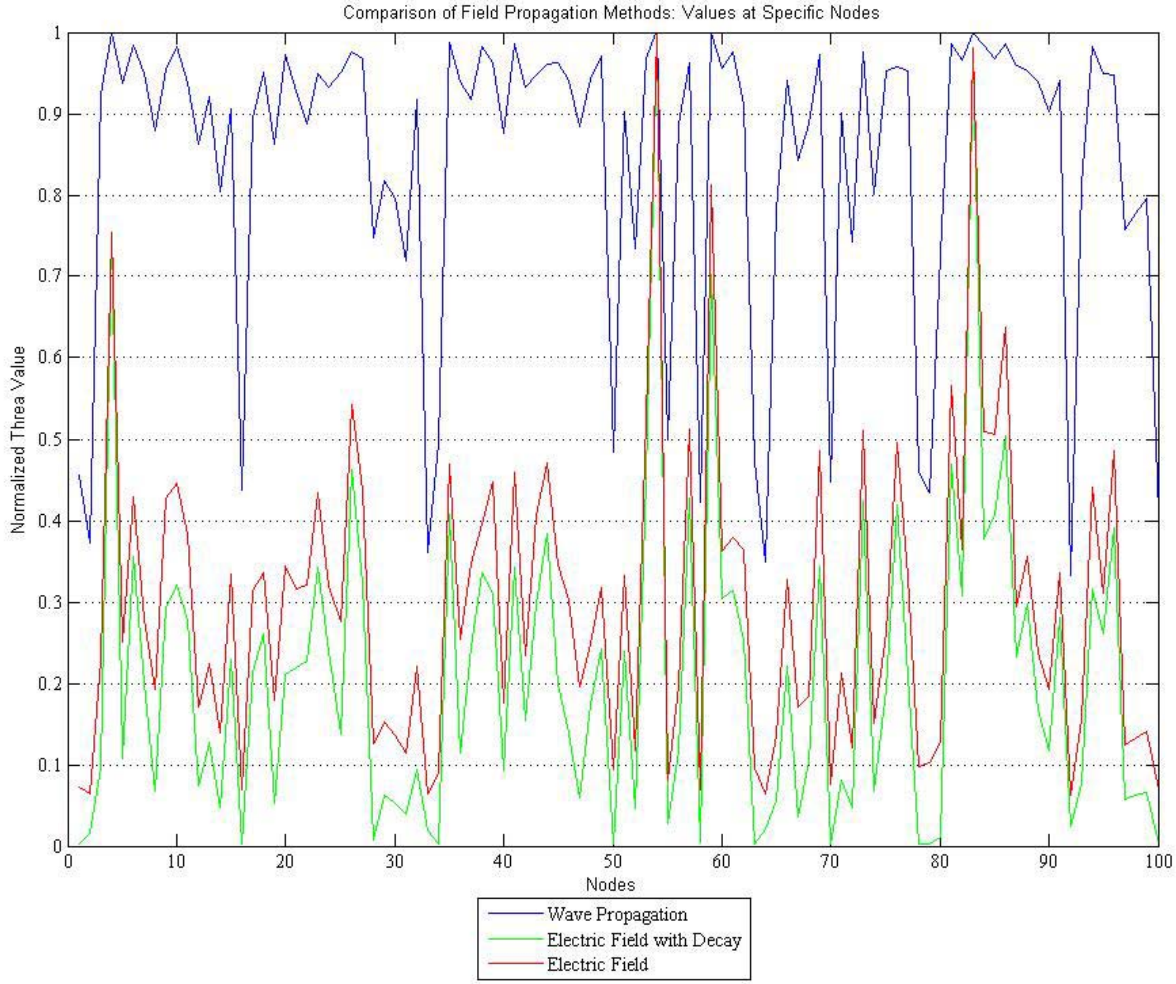
Discrete Choice

- Based on neoclassical economic theory that assumes the decision maker can conduct pair-wise comparisons.
- If that can be done then an ordered set may be formed.
- The Luce model builds off of this by assigning a probability that a choice is made instead of assigning one outright.
- This probability is calculated by dividing a unique valued function for the choice from the set by the sum of that function for all the choices from the set.
- Random utility theory helps determine how others value each choice relative each other by assigning a deterministic and stochastic component to each choice.

Discrete Choice

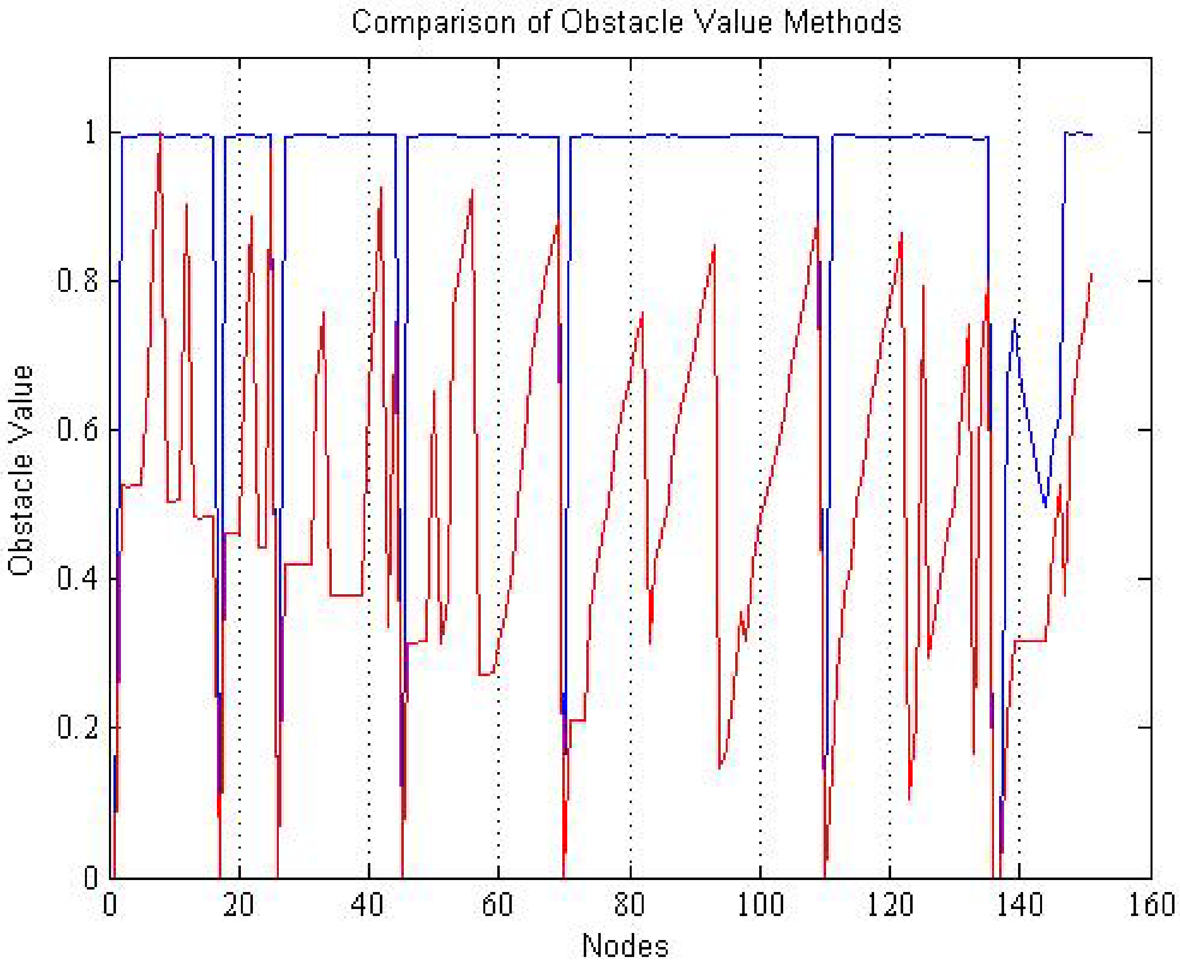
- The Probit model named that stochastic component as normally distributed error leading to a non-closed form solution to the problem.
- The Logit model changed that stochastic component to a Weibull distributed error. This leads to a closed form solution to find the probability. The unique valued function becomes the exponential of the utility and the equation takes the form shown on slide 13.

Differences in Threat Score Based on Method Choice



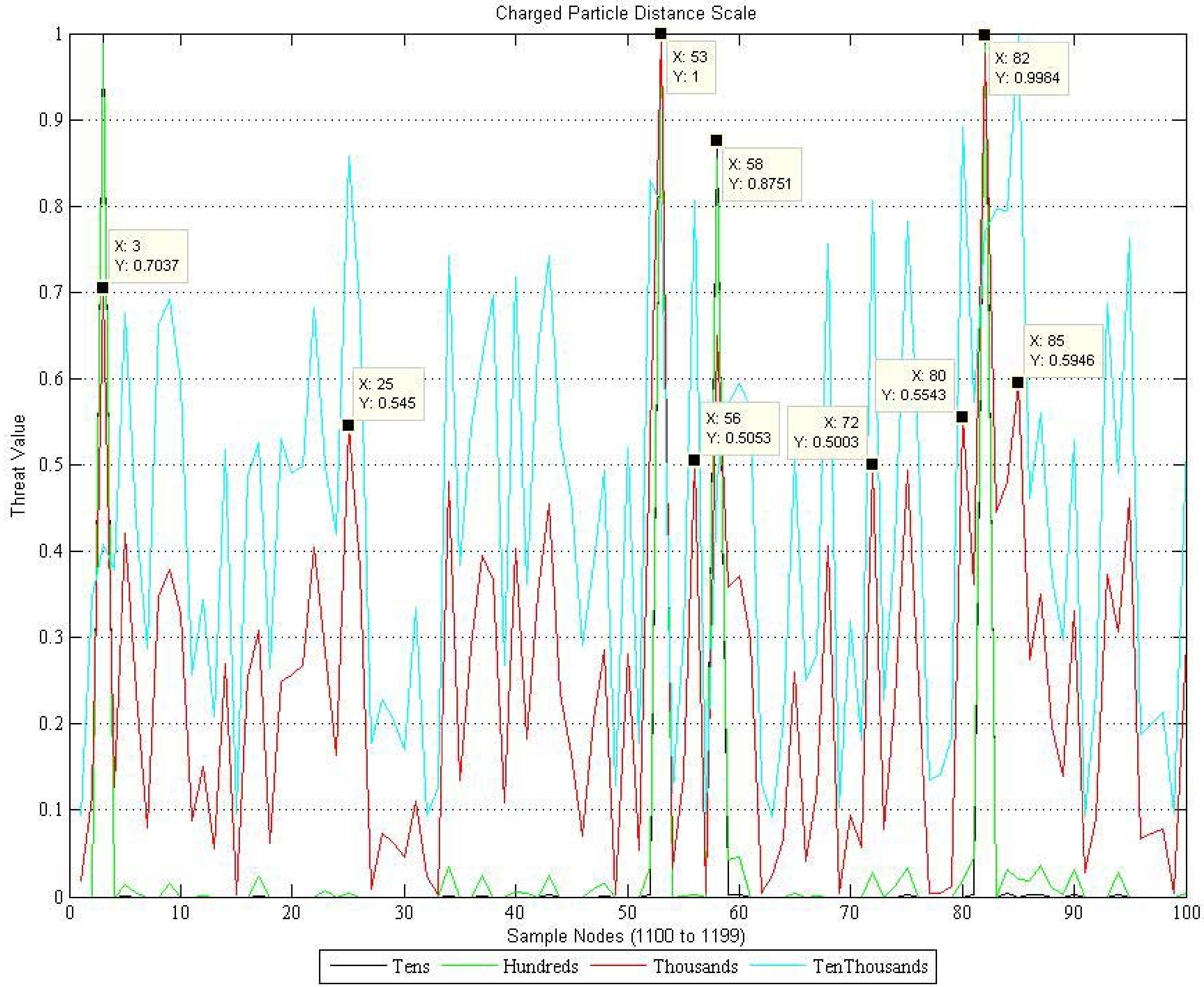
Back

Obstacle Score Method Comparison

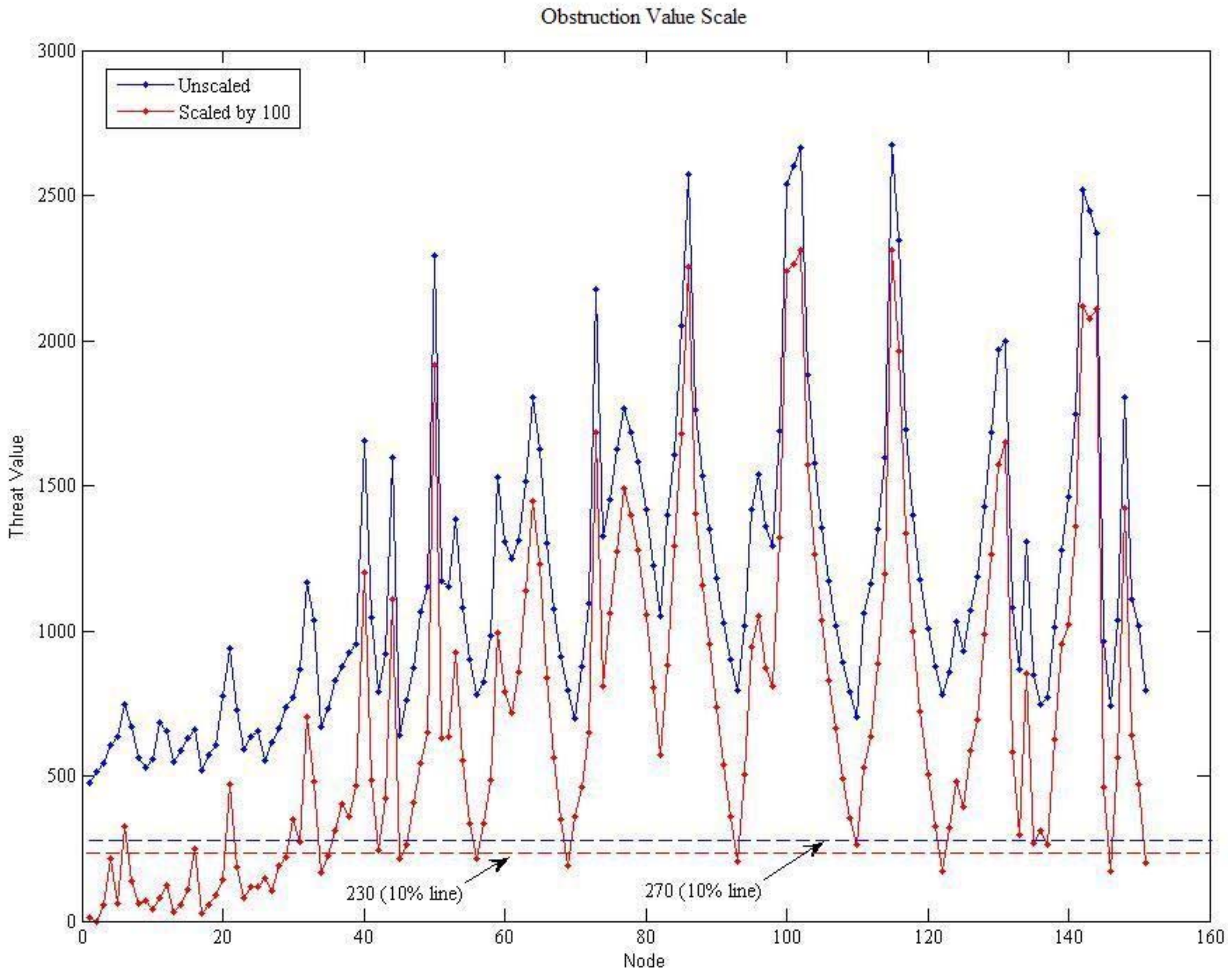


Back

Charged Particle Distance Scale



Obstruction Value Scale



Back

Proposed Approach (10 of 12) – Optimization algorithm

- Once the firing point is determined an informed search algorithm is used to determine the shortest path.
- A*, originally developed by Hart, Nilsson, and Rapheal in 1967, is guaranteed optimally efficient for networks.
- In order to get the *k-best* paths, removed nodes from the path systematically based on their threat score.
- Creates a very good spread of routes from the source to the goal.

Proposed Approach (11 of 12) – Discrete Choice

- To determine the probability that an insurgent or terrorist would use a particular path, Logit choice was used.
- Logit choice makes the calculations quick and accurate providing a good relative reference between the different paths that the insurgent or terrorist would use.