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

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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.

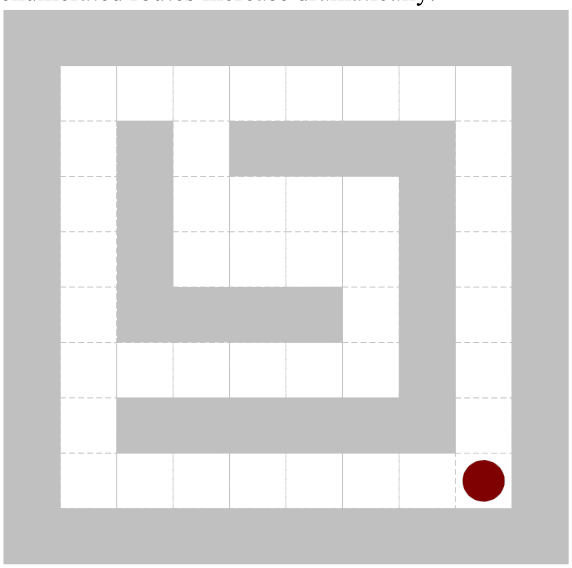

Figure 1. Employing an equal expansion along each path and branching as necessary will enumerate the entire space.

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.

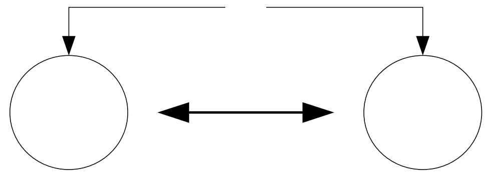

Figure 2. The force that charged particles exert on one another is proportional to size of the charge and the distance between them squared. If the charges have the same sign then it is a positive (repulsive) force. If the charges are opposite, it is a negative (attractive) force.

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.

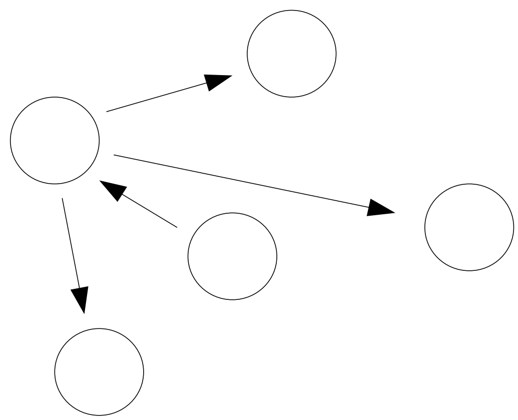

Figure 3. The unresolved forces on charge 1 from the other charges.

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.

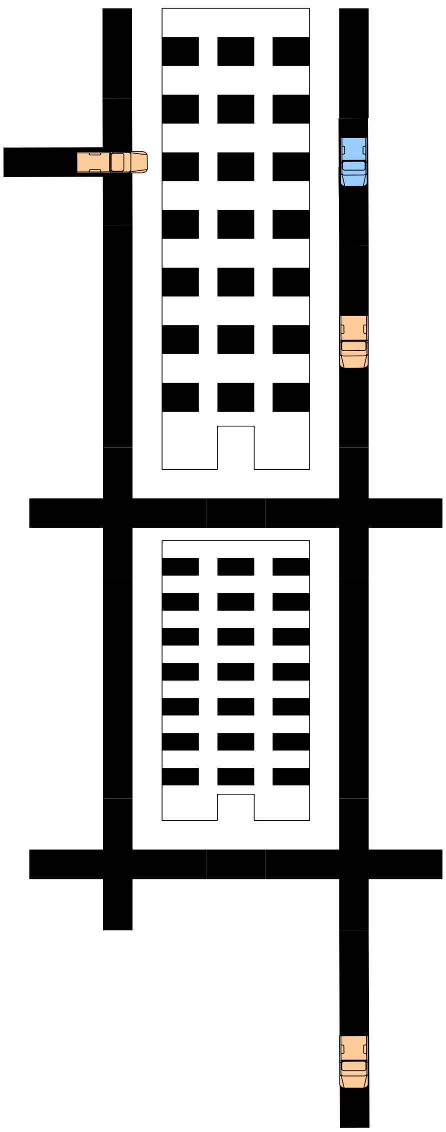

Figure 4. Illustration of the influence of the CP over terrain.

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.

Node \ Node	1	2	3	4
1		1		3
2	1		2	4
3		2		5
4	3	4	5	

Arc Number

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.

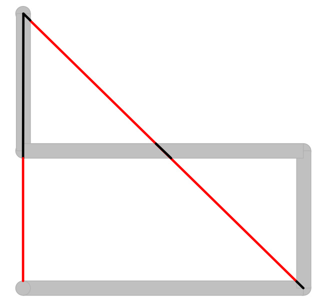

Figure 6. The red portions of the line are elements that contribute to the obstruction value.

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.

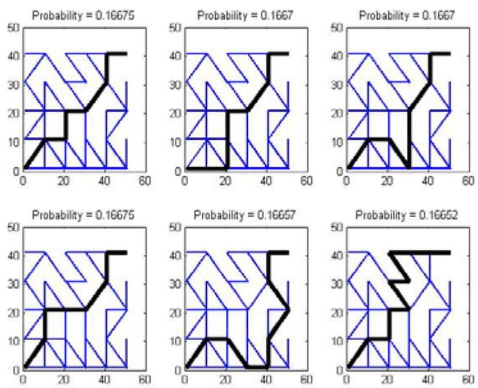

Figure 7. Sample output of network with the six (k) best paths outlined and their associated relative probabilities.

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.

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