Terrain-Based Information Fusion and Inference

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Abstract- *A key prerequisite for higher-level fusion is the use of context to disambiguate and interpret sensed data and guide data collection. For ground operations terrain information supplies an important context. The layout of terrain is a determining factor in arraying of forces, both friendly and enemy, and the structuring of Courses of Action (COAs). For example, key terrain, such as a bridge over an un-fordable river, or terrain that allows observation of the opposing forces line of advance, is likely to give a big military advantage to the force that holds it. Combining information about terrain features with hypotheses about enemy assets can lead to inferences about possible avenues of approach, areas that provide cover and concealment, areas that are vulnerable to enemy observation, or choke points. Key terrain identifies areas where intelligence collection effort should be focused. In addition, if force movements are observed, terrain features give additional information with respect to the intent of enemy forces that have been observed on the move, thus confirming or disconfirming hypotheses about enemy intent. Currently, intelligence officers manually combine terrain-based information, information about the tactical significance of certain terrain features as well as information regarding enemy assets and doctrine to form hypotheses about the disposition of enemy forces and enemy intent. In this paper, we present a set of algorithms and implemented tools for automating terrain based information fusion and inference. The products of automated terrain analysis are currently being validated using analysis of the same terrain produced by human intelligence officers.*

1. Introduction

The particular type of terrain on which ground operations are conducted is a key determining factor of the types of operations and arraying of forces both for friendly and enemy forces, Terrain provides important context for analysis of sensed data as well as for guiding the tasking of data collection assets. The importance of the study and analysis of terrain has been recognized for hundreds of years in military science. Currently, such analysis is called the Intelligence Preparation of the Battlefield (IPB). IPB is a process that starts in advance of operations and continues during operations planning and execution. It provides guidelines for the gathering, analysis, and organization of intelligence. The purpose of this intelligence is to inform a commander's decision process during the preparation for, and execution of a mission.

The resulting products of IPB are identification of various areas of the battlefield that affect Courses of Action (COAs). Such distinctive areas include engagement areas, battle positions, infiltration lanes, avenue of approach etc. For example, an un-fordable river is an obstacle, i.e. a terrain feature that impedes or prevents the maneuver of forces. Identification of such terrain features is invaluable since it allows the commander to make inferences about possible enemy avenues of approach and degree of vulnerability of his own force to enemy attacks. Such information, combined with information about possible enemy assets and force structure, e.g. tank platoon, or company or battalion, provide measures of *ease of movement (trafficability)* of forces throughout the terrain.

Key terrain is any location whose control is likely to give distinct military advantage to the force that holds it. Key terrain examples include road intersections that connect with a force's line of communication; a bridge over an un-fordable river; or terrain that affords observation of the opposing force's line of advance. Key terrain areas cannot be defined by geographical features alone. The evaluation of terrain features must be fused with information about weather, enemy asset types, friendly and enemy range of fire, enemy doctrine and type of operation (e.g. defensive or offensive). For example, if an enemy tank company has been observed on the move towards an un-fordable river, the presence of that river is not necessarily an obstacle if the company has an associated corps of engineers who could easily construct a bridge to allow passage. Hence the presence of the corps of engineers is a key element in a commander's threat assessment and evaluation. It is crucial for a commander to know whether enemy forces have occupied or are about to occupy key terrain. Therefore, key terrain areas identify areas where intelligence collection efforts should be focused.

An analysis of *concealment* provides areas that offer protection from observation and an analysis of *cover* identifies areas that offer protection from fires. The analysis of the terrain's suitability for providing concealment and cover result in the identification of *defensible terrain*. Fusing information about ranges of weapons with information on areas that provide poor concealment and cover identifies *engagement areas*: such areas are to be avoided by an attacking force, whereas they are potential engagement areas for a defending command. Therefore, the identification of defensible terrain and engagement areas is an important component supporting adversarial intent inference. To this end, engagement areas indicate areas where it is very useful to concentrate activity of collection assets.

As has been argued above, the products of the IPB process provide a number of crucial constituent elements for high-level information fusion (levels two, three and four). First, they provide a context within which to interpret the military value of various terrain features and other concomitant pieces of information. Second, they provide a set of high-level conceptual abstractions (e.g. ease of force movement, concealment, cover, engagement areas) that could be used as the elements of a language to describe high level information fusion processes and results. Third, they provide guidance as to the types of information to be fused and particular high-level inferences that can be made. Fourth, they provide particular, focused guidance for tasking collection assets.

Currently intelligence officers using hardcopy maps do IPB manually by making notations of various significant areas, such as key terrain or defensible terrain. This manual process suffers from a number of inefficiencies: First, the hardcopy maps do not allow variable zooming in and out to obtain desired level of detail in an integrated, fast and consistent manner. Second, manually annotating the maps is time consuming. Third, notations on maps get cluttered with the risk of being misread, especially in the stressful times during operations. Fourth, depending on the experience and ability of individual intelligence officers and due to cognitive overload, various pieces of information could be disregarded or not used effectively in the process of the Intelligence Preparation of the Battlefield. Therefore, decision support tools that automate part of the process are highly needed.

Development of such decision support tools faces many challenges. First, computational algorithms must be developed to transform low level terrain information, e.g. soil types, vegetation, elevation slopes to higher level notions such as maneuverability of a force, engagements areas, defensible terrain etc. Second, appropriate cost schemes must be developed to allow expression of degree of strength of particular concepts of interest, for example degree of concealment that is afforded by a particular area. Third, since the IPB process is ongoing, spanning pre-operational activity and continuing throughout an operation, the computational algorithms must be efficient. Fourth, effective rule bases must be developed to allow combination of different pieces of terrain-based information with information about assets, weather, doctrine and results of sensors. Fifth, a user-friendly and flexible GUI must be developed for user interaction.

In this paper, we present an a set of representation schemes and implemented algorithms that aim to (a) support intelligence officers in the IPB process and high level fusion inferences, (b) inform the process of COA generation, and (c) support the process of tasking intelligence collection assets. We have planned a set of experiments that will validate the results of the automated tools in comparison with results produced manually by human intelligence officers.

The rest of the paper is organized as follows: Section 2 presents an overview of the IPB process, its products and the role these products may play in the C4I process. Section 3 presents the representation schemes and computational algorithms for automating the reasoning for various aspects of terrain analysis. Section 4 presents conclusions.

2. Overview of Intelligence Preparation of the Battlefield (IPB)

IPB is a cyclical process that continues throughout the planning and execution stages of a mission. The goal of IPB is to guide the collection, organization and use of intelligence. IPB products identify areas in the terrain where intelligence collection efforts should be focused in order to discern the intent of the opposing forces commander. IPB has the following steps:

(1) define the battlefield environment: the product of this stage of IPB is the definition of the commander's area of operations (AO). The AO is the section of the battlefield that a commander has authority to conduct operations in. The AO encompasses any objectives that are essential to the completion of the commander's mission, as well as any enemy forces that could have an influence on the successful completion of the mission.

(2) describe the battlefield effects: at this stage terrain analysis and weather analysis are performed in the AO in order to identify their effects in the operation of friendly or enemy forces. The initial product of this step is the Combined Obstacle Overlay (COO). Combining the COO with Key Terrain, Defensible Terrain, Engagement Areas, and Avenues of Approach results in the Modified Combined Obstacle Overlay (MCOO), which is the final product of this IPB phase. The features in the MCOO are high-level terrain-based concepts of crucial tactical significance.

(3) evaluate the threat: threat evaluation is the identification of the capabilities of the opposing forces in conjunction with knowledge of enemy doctrine and tactics. The products of this stage of IPB are threat models. Threat models consist of doctrinal templates, description of enemy tactics and identification of high value targets. Doctrinal templates are graphical representations of the deployment patterns and dispositions preferred by an opposing force while conducting standard operations (assembly, defense, movement to contact etc.) under various circumstances. It is important to note that doctrinal templates represent force deployment without regard to the limitations of terrain. When used for inferring an enemy's intent it is necessary to cross reference with the MCOO to consider how the terrain would force deviation.

(4) develop potential enemy courses of action (COAs): a course of action is a detailed plan for the accomplishment

of a mission, including the arrangement and deployment of forces both spatially and temporally necessary for successful mission completion. This is the main stage of intent inference. The input to the COA generation process is hypothesized enemy objectives, suspected enemy locations, threat models and the MCOO. The output is several hypothesized enemy COAs. During the development of enemy COAs, a commander attempts to infer enemy intent by hypothesizing several COAs that would lead to an enemy suspected objective. The commander, after performing terrain evaluation using the MCOO, and combining these evaluations with information from the hypothesized COAs, will identify areas in the terrain, called *named areas of interest* (NAI), such that enemy activity reported from these areas will confirm or deny his hypotheses about the enemy's current COA. NAIs are the areas where a commander will concentrate his intelligence gathering efforts, both before and during operations.

3. Automating MCOO Development

This section describes our representation schemes and algorithms that aim to provide computational tools to support intelligence officers in the process of MCOO construction.

3.1 Trafficability

Fig. 1 shows separate overlays, each of which depicts un-trafficable terrain due to the following factors.

- Vegetation and soil type
- Weather and surface drainage
- Slopes
- Minefields
- Trenches
- Bodies of water

These are combined to form an overlay that shows all obstacles.

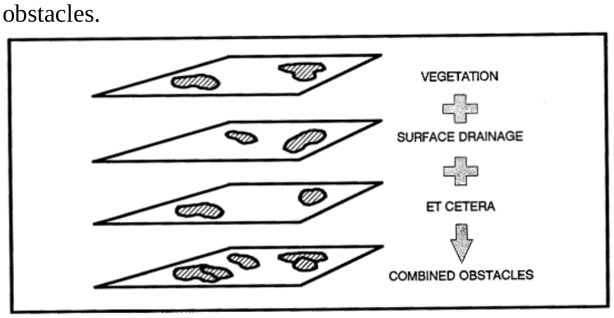

Fig. 1. Obstacle overlays combined to form COO.

We use as our terrain representation the Compact Terrain Database (CTDB) format used by the OneSAF Testbed Baseline simulation software [10]. The CTDB format gives us access to a grid of elevation values as well as an associated soil type for each grid cell.

We use the elevation grid to calculate both slope and surface configuration. Surface configuration refers to whether a grid cell lies on a flat surface, a concavity like a hill, or a convexity like a trench. This calculation is necessary because it allows us to judge the effects of precipitation on a certain grid cell. Rain, for example, is much less likely to affect the trafficabilty of a region that lies on top of a small hill than it would a previously dry riverbed.

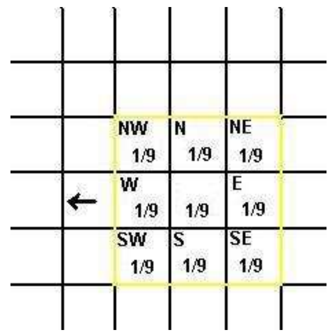

Fig. 2. Mean smoothing filter kernel.

To find surface configuration the window or kernel shown in Fig 2 is used as a mean smoothing filter. A smoothed elevation surface is the result of discrete convolution of the original elevation surface with the kernel according to Eq (1), where (O) is the smoothed grid, (I) the original grid, and (K) the kernel.

$$O(i,j) = \sum_{k=1}^{3}\sum_{l=1}^{3} I(i+k-1, j+l-1)K(k,l) \quad (1)$$

The surface configuration for a given grid cell is then the result of subtracting the grid cell values of the smoothed surface from the corresponding grid cells on the original surface [9]. Convexities are identified as a negative difference between the actual and smoothed surfaces while concavities are positive. This process is illustrated in Fig 3.

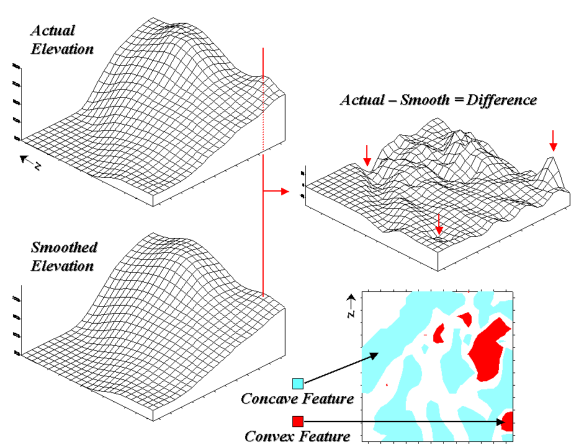

Fig. 3. Surface configuration calculation.

This works because the grid cells of the smoothed elevation surface represent the trend in elevation of the surrounding area. This means that subtracting the smoothed grid from the original elevation grid results in a grid with cell values that represent the variation from the trend of the surrounding cells. The slope at grid cell (x,y) is assigned the mean of the slope between (x,y) and each of the eight surrounding grid cells shown in Fig 2.

The pseudo-code shown in Fig. 4 illustrates the calculation used to find trafficabiliy for a grid cell on our terrain map. The first section simply checks that the soil type of the grid cell is not of a clearly untrafficable type like deep water. The next section determines the presence of vegetation. Vegetation in OTBSAF's CTDB database is limited to tree canopies so at this point the tree spacing is assessed to determine if it is sufficient for the given vehicle type to pass. Next the slope of the grid cell under consideration is compared to the maximum trafficable slope for the given vehicle type. If the slope is less than this value, the slope is passed on to a vehicle speed calculation where it is used as a multiplier for the base vehicle speed. The base vehicle speed is the vehicle's maximum speed on flat terrain for the given soil type. The speed also takes into consideration weather and surface configuration. If the surface is convex and there is precipitation then the speed calculation uses the wet soil type value. Otherwise the dry soil type value is used.

```
Trafficability(x,y,vehicle){
  stype = SoilType(x,y)
  slope = GetSlope(x,y)
  max_slope = MaxPassibleSlope(vehicle)
  weather = GetWeather(x,y)
  surfaceconfig = GetSurfaceConfig(x,y)

  if stype(x,y)== bolders or deep_water
    SetTrafficability(x,y,NO-GO)

  elseif stype == canopy_forest
    if TreeSpacing(x,y) < min_spacing
      SetTrafficability(x,y,NO-GO)
    else
      SetTrafficability(x,y,SLOW-GO)

  elseif slope > max_slope
      SetTrafficability(x,y,NO-GO)

  else
    slopemult = percentSlope(slope)

      speed=CalcSpeed(vehicle,
              slopemult, wet, stype)
    else
      speed=CalcSpeed(vehicle,
              slopemult, dry, stype)
    if speed ≤ NO-GO-SPEED
      SetTrafficability(x,y,NO-GO)
    elseif speed ≤ SLOW-GO-SPEED
      SetTrafficability(x,y,SLOW-GO)
    else
      SetTrafficability(x,y,GO)

}
```

Fig. 4. Trafficability pseudo-code.

The NO-GO and SLOW-GO terrain become obstacles that are used as input for the algorithms described in the remainder of the paper.

The authors in [3] use qualitative spatial reasoning to determine the trafficability of a grid cell. This allows a system determining trafficability to give a reasonable answer when information for some regions is missing. We decided to use a purely computational model of trafficability because our focus is on the automation of the determination of higher-level terrain features, such as engagement areas and defensible areas.

.3.2 Configuration Space

The COO tells us at a glance the ease of movement for a given vehicle type through a certain grid cell on a terrain. This is suitable for a single vehicle but does not capture certain phenomena associated with multi-vehicle travel. This is important because military vehicles are apt to travel en masse. An example of such a phenomenon is the bottleneck effect. This is the tendency of a pack of vehicles to slow down while moving through a narrowing corridor. The reduced speed caused by narrow corridors or canalizing terrain also makes traveling military units more vulnerable to attack. For this reason terrain analysts enhance the COO by identifying canalizing terrain throughout an area of operations. We have enhanced the COO in a similar way by using the idea of Configuration Space, traditionally used in path planning for mobile robots.

Consider a tank platoon traveling through a piece of terrain. The NO-GO regions of the terrain are obstacles to the movement of the platoon and can be represented as polygons. We can also represent the tank platoon with a polygon as shown in Fig 5. The same figure also shows a reference point for the platoon.

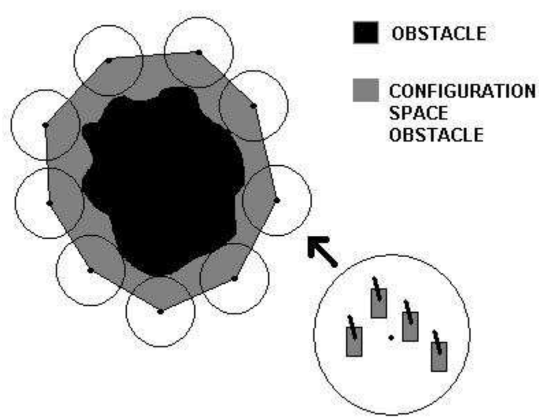

Fig. 5. Configuration space obstacle.

If we place the reference point for our tank platoon on a grid cell such that the tank platoon polygon overlaps an obstacle, then this grid cell is a part of a Configuration Space or C-space obstacle. Grid cells where such placements do not result in an overlap are a part of free space. In C-space obstacles appear as expanded versions of the obstacles from which they were derived. We can visualize this by placing the platoon polygon against an obstacle and tracing its reference point around the obstacle. This is illustrated in Fig 5. Because of this expansion, sometimes obstacles that are separate will merge in C-space.

We have thus far talked about using a polygon that represents a tank platoon. We could just as easily use these methods to find the C-space obstacles relative to larger units like companies or battalions. If we choose the dimensions of our unit polygon to reflect the minimum vehicle spacing that is conducive to safe and efficient travel we can obtain the following information from our C-spaces. If a point in the C-space corresponding to a given unit lies within a C-space obstacle this means that the corresponding location within the terrain is too canalizing to allow the unit to pass safely.

Fig. 6 shows the superimposed C-space obstacles for several different force echelons. Notice how the calculation highlights the narrow passages shown in the figure. The color codes, or grayscale if this document is viewed in black and white, represent the frontage of a unit that can pass comfortably. This simple calculation allows a viewer to quickly extract richer information about the area of operations than would have been possible from the traditional COO without further human analysis.

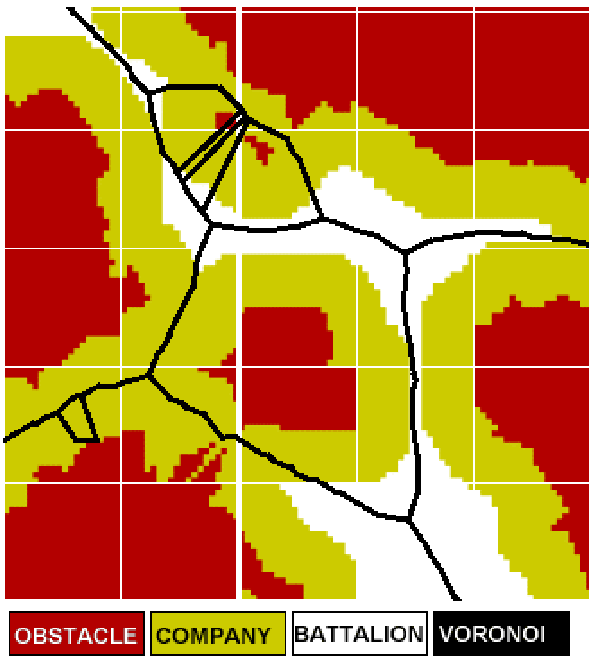

Fig. 6. GVD with configuration space obstacles.

C-space obstacles are calculated by taking the Minkowski Sum of the platoon polygon and an obstacle polygon. The definition of the Minkowski Sum for two polygons A and B, with vertices $v \in \Re^2$ and $w \in \Re^2$ respectively, is shown in Equation (2).

$$A + B = \{v + w \mid v \in A, w \in B\} \quad (2)$$

In practice the calculation of the Minkowski Sum is greatly simplified and much more efficient if both input polygons are convex. For this reason we first take our obstacle polygons which are not convex and triangulate them. We calculate the Minkowski Sum of the platoon polygon with each of the triangles and then merge the results.

3.3 Voronoi Diagram

In [4] the authors make the observation that the properties of the Voronoi diagram make it an excellent starting point for expressing the topology of the unrestricted regions of the COO.

The following definition of the Voronoi diagram is obtained from [1]. The Euclidean distance between two points p and q in the plane is denoted by *dist(p,q)*:

$$dist(p,q) = \sqrt{(p_x - q_x)^2 + (p_y - q_y)^2} \quad (3)$$

Let $P = \{p_1, p_2, \ldots, p_n\}$ be a set of n distinct points or sites in the plane. The Voronoi diagram of P is the subdivision of the plane into n cells, one for each site in P, with the property that a point q lies in the cell corresponding to a site p_i if and only if $dist(q,p_i) < dist(q,p_j)$ for each $p_j \in P$ with $j \neq i$.

If the sites are replaced with polygons, the above definition holds true with a more complex distance function that represents the minimum distance between a point and a polygon in the plane. Such a diagram for polygons instead of points is called the Generalized Voronoi Diagram (GVD). Choset et al provide an excellent description of the distance function for the (GVD) in [7].

Fig. 6 shows a GVD calculated using the NO-GO regions of a heavily restricted COO. Notice how GVD edges correspond with mobility corridors through the terrain while GVD vertices occur in enclosed regions. These properties lend themselves to finding avenues of approach, defensible areas, and other important tactical features of terrain. The MCOO is a result of computationally inferring these important tactical high-level concepts and combining them with the COO. We will illustrate this in later sections.

The GVD is expensive to calculate exactly. Fast execution time of our algorithms is paramount because we seek a system capable of reanalysis in keeping with the high tempo of battle. For this reason we calculate an approximation to the GVD. The approximation is found by sampling the outlines of the NO-GO polygons. We calculate the Voronoi diagram of the resulting sample points. Next we obtain an approximation to the GVD by removing any Voronoi edges that have an endpoint in a obstacle.

Circuit Representation

Our representation is a skeletonization of terrain. The paths throughout the terrain have been reduced to the one-dimensional edges of the GVD, which encodes the topology of the terrain. From the GVD we can identify mobility corridors as edges and enclosed regions as vertices. Furthermore, with the GVD superimposed onto the merged C-space obstacles, the dimensions of the mobility corridors and enclosed regions around the terrain can be associated with edges and vertices. This in turn gives an indication of the unit sizes that can utilize certain regions and corridors.

It can be argued that a study of the military aspects of terrain is a study of its resistance: both the natural resistance the terrain affords, as well as how well the terrain supports enhancing its natural resistance through the emplacement of weapon systems. A study of the terrain from a defensive standpoint is a study of what areas best provide resistance to an encroaching enemy while a study from an offensive standpoint aims to find the weak points in the enemy's ability to apply resistance. This along with the network like appearance of our terrain GVD suggests an analogy to circuit theory.

Fig. 7 (a) shows a piece of restricted terrain with obstacles in black and (b) shows the associated graph representation of this section of terrain. Fig. 7 (c) shows this corridor network, as a circuit with an associated resistor for each corridor that is representative of the resistance a unit would face while attempting to navigate it. This resistance is proportional to the length of a corridor and inversely proportional to its width.

Eq. (4) is a statement of Ohm's law, which relates the basic circuit quantities of Voltage (V), current (I), and resistance (R).

$$V = IR \quad (4)$$

$$I = \partial Q / \partial t \quad (5)$$

Eq. (4) defines current as the rate of flow of charge (Q). The flow of charge is due to the motion of electrons, so current through a wire can also be thought of as the rate of travel of physical objects (military forces) through a passage.

In the next subsections we briefly discuss how the circuit heuristic can help a system automatically identify and select regions of the terrain as engagement areas, defensible areas, and determine avenues of approach to an objective. The obvious benefit to this approach is that off the shelf circuit analysis software could be used to quickly analyze the military aspects of a piece of terrain.

Engagement Areas

The army field manuals tell us that a terrain analyst will consider cover and concealment while determining the suitability of a region as an engagement area. The field manual also tells us that enclosed regions are favored.

We can construct a list of candidate engagement areas using the terrain representation described in sections (3.1-3.3). The GVD vertices are prime candidates because they naturally occur in enclosed regions. A line of sight analysis between the location of such a vertex and its surroundings will assess the amount of cover and concealment available. Higher ratings would be given to areas with poor cover and concealment.

There might be many candidate engagement areas in a piece of terrain under analysis. In practice a military force is unlikely to have the resources to use them all. It is necessary to select some of them.

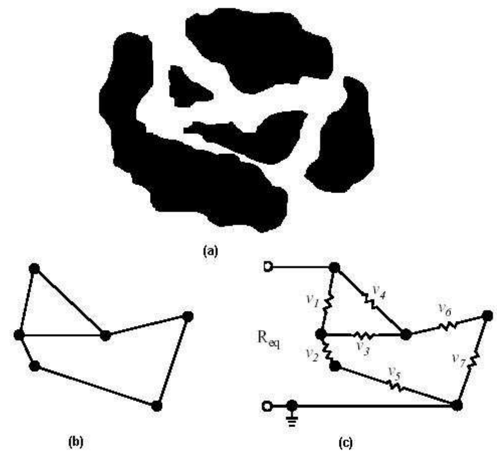

Fig. 7. Circuit representation of restricted terrain.

One approach to engagement area selection is to pick the (*n*) candidate regions with the highest ratings based on cover and concealment. The drawback of this selection approach is that this would not take into consideration the topology of the terrain. This is where our circuit representation becomes useful. We would like to automatically select engagement areas that would best disrupt enemy travel throughout the entire region. Consider trying to select engagement areas in the terrain shown in Fig. 7(a) so as to disrupt enemy approaching from the SE corner while defending the NW corner. Based on our circuit analogy if we assign corridor resistances appropriately then the net current flow between the terminals of the circuit shown in Fig. 7(c), for a constant voltage, is a baseline measure for the ease with which an enemy can travel between the SE and NW without manned engagement areas. Our system can then hypothesize manning combinations of engagement areas by increasing the appropriate resistances. A comparison of the resulting current flow between the terminals to the baseline value would then be a measure of how disruptive the choice of engagement areas would be to the movement of the enemy.

Avenues of approach

An *avenue of approach (AA)* is a route that an attacking force can use to reach an objective. Features that must be considered in the evaluation of AA's are

- Degree of canalization (presence of choke points)
- Sustainability (access to a line of sight)
- Availability of Concealment and Cover
- Obstacles

Avenues of approach can be found using a technique similar to that used to find engagement areas. In this case the resistance of candidate engagement areas is increased if the commander suspects that the enemy might use them. The mobility corridors with the highest current flow would then be chosen as a part of the avenue of approach. We could find avenues of approach using traditional path planning approaches like A* search. However, traditional path planning would identify only a single path through the terrain. This might result in the identification of avenues of approach that are too canalizing in places. If a single mobility corridor is too canalizing then it is better to use several at once as a part of an avenue of approach as shown in Fig. 8.

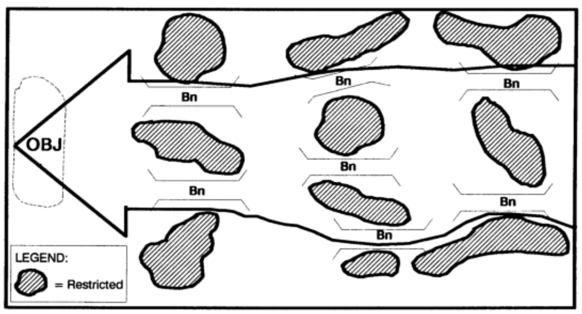

Fig. 8. Mobility corridors grouped to form an avenue of approach.

One potential drawback of this approach is that mobility corridors that are physically far apart may have the least resistance and hence the highest current. In practice if splitting forces is necessary due to canalizing corridors it would probably be safer for a force to use corridors with close proximity. One possibility of dealing with this problem is to find a central axis of an avenue of approach using A* search. The resistance of other corridors could then be increased proportionally to their separation from the central axis. This would result in higher currents in corridors that are closer together.

Defensible terrain

A military force in a defensive posture is interested in ensuring security in all directions. To this end, a terrain analyst will seek out candidate defensible areas by the amount of natural protection they afford to as much of the defending force's perimeter as possible.

$$R = R1 + R2 \quad (7)$$
$$R = R1*R2 / R1+R2 \quad (8)$$

In electrical circuit theory two resistors in series with resistance R1 and R2 can be replaced with a single resistor according to Eq. (7). Resistors in parallel can be replaced by a single resistor according to Eq. (8). By recursive application of these equations, an entire circuit of resistors can be replaced by a single resistance. By applying these rules to our circuit representation of terrain, the single resulting resistance can be used to measure the defensibility of a region.

4. Validation

Two subject matter experts (SMEs) with extensive field experience in intelligence analysis were recruited from the ROTC staff at the University of Pittsburgh for initial validation of our approach. The SMEs were videotaped and provided think-aloud verbal protocols while filling in MCOO overlays for maps generated from CTDB data.

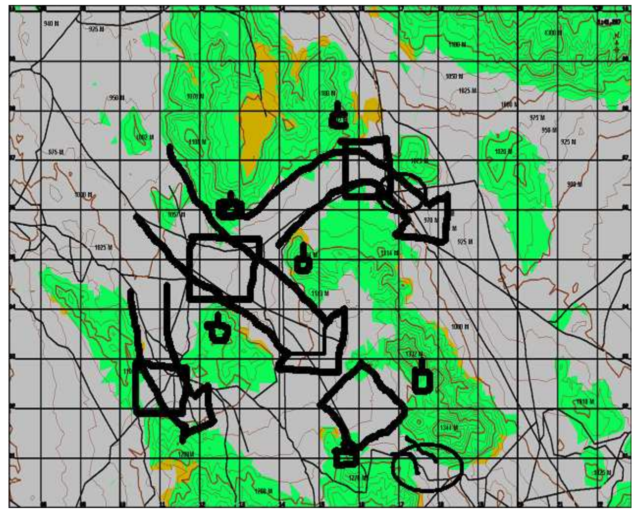

Fig. 9. MCOO constructed by SME-1

Fig. 10. MCOO constructed by program

Fig. 9 depicts the major annotations made by SME-1 on the MCOO overlay. The double-headed arrow indicates the primary AA. Single headed arrows denote the secondary AAs. The boxes represent engagement areas and the smaller boxes with lines indicate named areas of interest (NAIs). The results of the analysis by our terrain analysis algorithms are shown below in Fig. 10. The regions marked with an X represent engagement areas. An arrow with a solid head denotes the primary avenue of approach while an arrow with a clear head denotes the secondary avenue of approach.

Our program chose the same primary avenue of approach as SME-2. This avenue of approach coincided with SME-1's choice as a secondary AA. This discrepancy between the program and SME-2's choice of the "Eastern route" and SME-1's choice of the more direct "Southern route" appears to lie in the SMEs' prior command experiences. Of the two paths circled in Fig. 9, the one closest to the bottom of the map is the most canalizing. SME-1 indicated that although this made the path more dangerous, the shorter path to the objective made the added risk acceptable. This reasoning was not available to the program because path length is considered only indirectly through its affect on resistance in determining ranking. The agreement between the program and SME-2 shows, however that even in its current stage of development our automated terrain analysis identifies avenues of approach within the range of variation among human SMEs.

There is good correspondence between our selections of NAIs with those of the SMEs. Of the eight NAIs identified, three were found by both SMEs and the program, two were identified jointly by SME-1 and the program, one was identified by both SMEs but not the program, and two singletons were found, one by SME-1 and the other by the program. The program again fell well within the range of variation of the SMEs matching more of the NAIs identified by SME-1 then did SME-2.

There is an exact correspondence between SME-1's choice of engagement areas and our algorithm's top 3 selections. The algorithm's 4th selection is positioned a small distance from this expert's final choice. This is because our program currently tries to pick candidate regions for engagement areas so that they control as many approaches as possible. The SME realized that two of the three paths entering this region had already been covered by previous engagement area choices. SME-2 chose a single engagement area that was among those chosen by SME-1 and the program. The discrepancies in SME-2's overlay seem to stem from an early choice of an extreme Eastern path as a secondary route. Because the "Southern route" was not chosen, NAIs and engagement areas along its path were considered less closely.

5. Conclusion

In this paper we presented representations and computational algorithms for providing automated support to military intelligence officers in the IPB process Experiments were conducted with human subjects who are military intelligence analysts and teach in the ROTC program at the University of Pittsburgh. The results of this validation effort suggest that automated terrain analysis shows promise for the replication of the identification of features identified by experienced intelligence officers in the process of preparing MCOO overlays. We plan to continue collecting data from several more analysts in order to establish an acceptable range of variability for different MCOO components allowing us to determine the degree to which the products of automatic terrain analysis match those prepared by expert human analysts.

Acknowledgements

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