Automating Terrain Analysis: Algorithms for Intelligence Preparation of the Battlefield

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Terrain information supplies an important context for ground operations. 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 unfordable 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. 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 tools for automating terrain analysis and compare their results with those of experienced intelligence analysts.

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 unfordable 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 unfordable 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 unfordable 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.

Currently, IPB is done manually by intelligence officers using hardcopy maps on which they notate 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 a set of representation schemes and algorithms developed for automated terrain analysis and compare their conclusions with those of experienced intelligence analysts.

AUTOMATING MCOO DEVELOPMENT

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. Terrain analysis is performed in order to identify the potential effects of terrain in the operation of friendly or enemy forces. The initial product of the analysis 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). The features in the MCOO are high level terrain-based concepts of crucial tactical significance.

Trafficability

Fig. 1 shows separate overlays, each of which depicts untrafficable terrain due to vegetation and soil type, weather and surface drainage, slopes, minefields, trenches, and bodies of water. These are combined to form an overlay that shows all obstacles. We use as our terrain representation the Compact Terrain Database (CTDB) format used by the OTBSAF simulation software. 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 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. The grid surface is smoothed and these regions identified as shown in Figure 2.

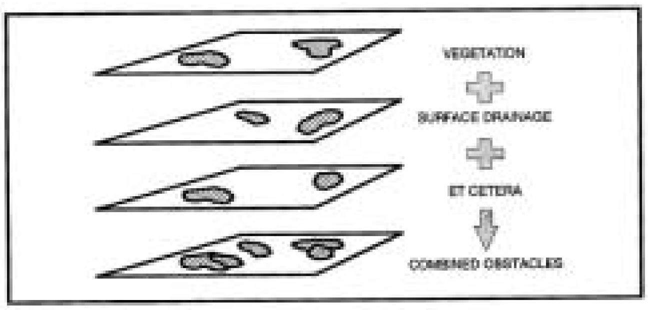


Fig. 1. Obstacle overlays combined to form COO

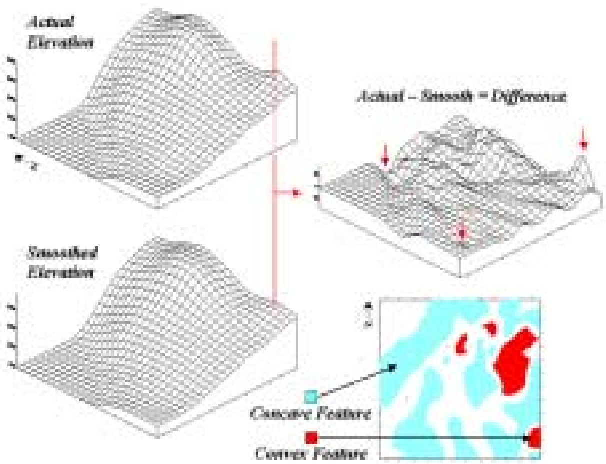
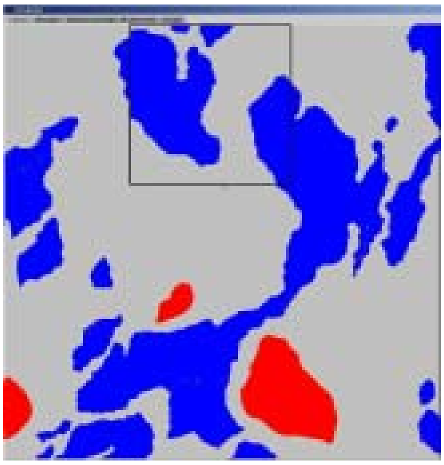


Fig. 2. Surface configuration calculation

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 concave and there is precipitation then the speed calculation uses the wet soil type value. Otherwise the dry soil type value is used. The result of the trafficability calculation is shown in Fig 3. Computational details for determining surface configuration and other aspects of automated terrain analysis are presented in (Glinton, et al. in press). The COO tells us at a glance the ease of movement for a given vehicle type through a certain grid cell on a terrain. If a corridor is too narrow to support travel in formation, however, the unit must change formation. The reduced speed and dispersed forces caused by narrow corridors or canalizing terrain makes units more vulnerable to attack. Our automated terrain analysis uses *configuration spaces*, a technique commonly used in path planning for mobile robots to identify these features. The Voronoi



Fig, 3. Result of trafficability calculation

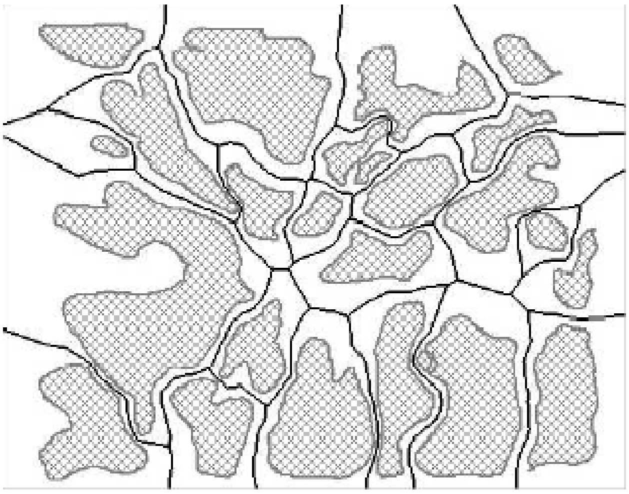


Fig. 4. Generalized Voronoi diagram of NO-GO regions

diagram, a common tool from computational geometry (de Berg et al., 2000) is then used to express the topology of unrestricted regions. Fig. 4 shows a generalized Voronoi diagram (GVD) (Choset, et al., 2000) 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 automating the identification of avenues of approach, defensible areas, and other important tactical features of terrain. By treating paths through this network as a circuit posing resistances through restrictive terrain and weapons emplacements defensive analysis becomes a study of what areas best provide resistance to an encroaching enemy while an offensive analysis aims to find the weak points in the enemy's ability to apply resistance.

Engagement Areas

The army field manuals instruct the terrain analyst to consider cover and concealment and favor enclosed regions in choosing engagement areas. The GVD vertices are prime candidates because they only occur in enclosed regions. A line of sight analysis between the location of such a vertex and its surroundings are used to assess the amount of cover and concealment available providing a first ranking. To choose among the many candidate engagement areas a circuit analysis is then used considering enemy movement along an expected axis such as from the SE corner to the NW corner of the operational area. By considering possible defensive manning allocations and the resulting resistance the engagement areas most disruptive to enemy movement can be identified.

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 are found using a technique similar to that used to find engagement areas. In this case the resistance of identified candidate engagement areas are increased. The mobility corridors with the highest current flow are then chosen as components of the avenues of approach.

Named Areas of Interest

Named areas of interest (NAIs) are areas of terrain that have particular tactical significance because they overlook potential engagement areas or canalized avenues of approach allowing the force that controls them early observation of enemy movements. While cultural features such as bridges can also qualify as NAIs, our approach is based on analysis of elevation and lines of sight to choose patches of ground that offer the broadest coverage of possible avenues of approach and engagement areas.

EVALUATION

Trial 1

Two subject matter experts (SMEs) with field experience in intelligence analysis were videotaped and provided think aloud verbal protocols while filling in MCOO overlays for a map generated from CTDB data. Their instructions for the portions of the task presented in this paper were:

> You are the S-2 of 1-22 Infantry battalion. Your battalion is located in the North West corner of this map. Your battalion is to seize an objective that is located in the Southeast corner of this map. You begin the Military Decision Making Process (MDMP) by doing terrain analysis and developing your MCOO. Please annotate the following: a) Slow-go/No-go terrain, b) Identify enemy engagement areas and potential defensible terrain (and the size of force that he could defend with), c) Named Areas of Interest (NAIs) (given that you will be moving from the Northwest to the Southeast), d) Display with a double arrow the path with the least terrain resistance and display with a single arrow an alternate path.

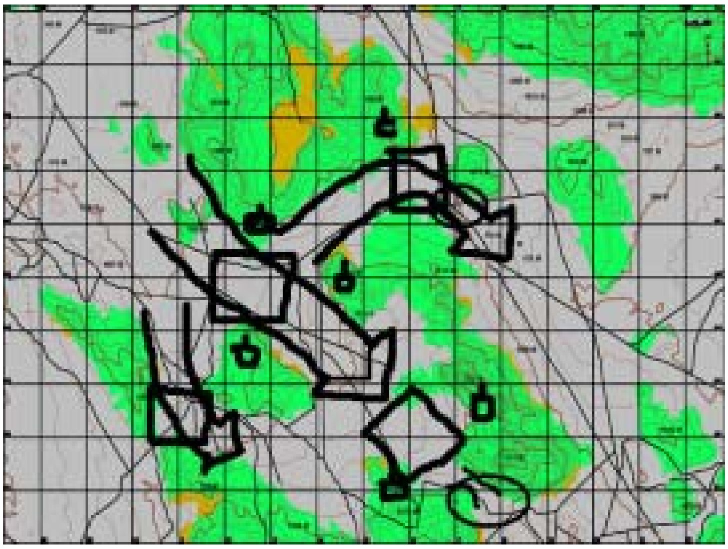


Fig. 5. MCOO produced by SME-1.

Fig 6. Automated MCOO

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primary avenue of approach. Single headed arrows denote the secondary avenues of approach. The boxes represent engagement areas and the smaller boxes with lines indicate named areas of interest (NAIs). The results of the analysis completed automatically by our terrain analysis algorithms are shown along side in Figure 6. 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 analysis 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 Figure 5, 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 its current stage of development our automated terrain analysis identified avenues of approach within the range of variation among human SMEs for this map. We hope to include facilities to allow users to interactively adjust cost functions to express such value judgments in the next version of our software. A solution as simple as a slide bar with safety on one end and speed on the other would allow the user to indicate the desired balance by positioning the slide bar to modify the weight given path length in path resistance calculations.

There is good correspondence between our selections of NAI's with those of the SMEs. However, the SME is limited by the granularity of the map. A physical map cannot be "zoomed in" to find some feature that does not appear at the resolution used for printing it. Our algorithms, however, can calculate line of sight between engagement areas and their

Figure 5 depicts the major annotations made by SME-1 on the MCOO overlay. The double headed arrow indicates the surroundings with high precision from high-resolution elevation data. For this reason our algorithms also produce more candidate NAI's. 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, the closest to the bottom of Figure 6, is positioned slightly differently 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. This suggests that we should consider topology in the selection of candidate engagement areas. Currently topology is only considered for culling the candidate engagement areas. 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.

Trial 2

The two SMEs from Trial 1 together with a third less experienced intelligence officer were asked to fill in MCOO overlays for four additional maps. The new maps were selected to investigate less constraining terrains and included a largely featureless desert, a flat area divided by a river, and two mixed maps with both highly constrained regions and large open areas. Performance and agreement were poorer than for the highly constrained terrain used in the first trial. Several SMEs commented that the desert map, in particular didn't give them anything to work with. The desert and river maps caused difficulties for the program as well because they lacked the obstacles needed to define regions in the Generalized Voronoi diagram. Although there was less agreement among SMEs than in Trial 1, the program's MCOO diverged from the SMEs' even more than they did from one another. Agreement with the program was strongest for the mixed maps where program and SMEs agreed closely on NAIs and engagement areas within constrained areas of the map but diverged for more open areas. In these open areas, as in the desert and river maps, the absence of anchoring obstacles led to identifying oversized engagement areas and wrecked havoc with the culling algorithm which was confronted with many uninformative intersecting regions defined by distant obstacles. Our experience with these sparser maps suggests that a divide and conquer strategy will be needed to automate IPB.

FUTURE DIRECTIONS

The circuit-based analysis of movement is the key concept behind our approach to automating IPB. Trial 1 demonstrated that in well constrained terrain using obstacles to define a GVR can provide a model of movement resembling that of a human expert. In open terrain, by contrast, the best path is not defined by avoiding obstacles but by choosing some especially low resistance path. Nevertheless there was substantial agreement among the SMEs

DISCUSSION

Our work in terrain analysis is ultimately meant to inform high-level information fusion. Only by capturing the context within which targets are identified and tracked can we attribute intent to their actions and guess at what else may be out there that we have not yet seen. Our early success in automating the MCOO process has exceeded our expectations and we are now extending the informal comparisons presented here with a full-fledged validation effort using a larger sample of SMEs with varying levels of experience and a larger collection of terrains.

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