High-Level Information Fusion and Mission Planning in Highly Anisotropic Threat Spaces

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Abstract – This paper presents a Command and Control (C2) agents approach to supporting tactical decision making by operational commanders. The work addresses two C2 issues: the use of networked information sharing and high-level information fusion to allow for the visualisation of highly anisotropic threat spaces, and associated route planning for a variety of effects based tasks taking into account a commander's immediate task needs, personal experience, and command preferences. We adopt wave propagation techniques used in seismology and present illustrations from a software suite we have developed that reflects commander preferences in effects routing, facilitates cooperative command planning, and analysis of opponent options.

Keywords: Information Fusion, Threat Map, Tactical Planning.

1 Introduction

We present a first report of a Command and Control (C2) approach to agents, a semi-automated information fusion, visualisation and planning system to understand how commanders' intentionality in a networked environment can be used to augment planning and execution in military tactical operations. Here, the work is considered primarily from the viewpoint of a decision support tool, intended to assist commanders in mission planning tasks, but it may equally be applied to a range of training and simulation activities, when interfaced with established tactical simulators, such as VR-Forces, OneSAF[1] or HiLOCA[2]. In the long term, this approach may find application in command driven Autonomous Fighting Forces (AFF) as a component part of the overall control mechanism.

This work addresses two contemporary C2 issues. First is using networked information sharing and fusion to create an explicit hypsometric (false-colour) *threat map* visualisation of the threats and hazards posed by elements in the current and potential situations, augmenting the conventional map information view. This provides commanders with an immediate and clear overall threat assessment at any place within the operational zone and any point within a complex mission. Threat is not evenly distributed over the operational space and we refer to this variability as *threat anisotropy*. We recognise that individual commanders often take a profoundly subjective view of specific situations based on their personal experience and personality (as evidenced in, for example, the work of Dodd *et al*, [1]) and we describe an information fusion mechanism to express the task intent and personality traits of the commander[3].

The second issue we address in this paper is providing a balanced hazard recommendation for a route to specific target locations within that operational zone. This takes the form of an immediate *threat level rating* and a *direction vector* indication coupled to an overall *preferred route* to the target, the time required to complete the manoeuvre and an estimated hazard profile. The route exposes weaknesses and opportunities within the opposing force's defensive structure, while balancing the commander's individual tactical preferences in relation to the threats faced.

Routes created by this process are not intended to be followed literally. Rather, they act as a recommendation for overall travel. The commander takes local decisions as required to avoid unmapped obstacles and hazards and to exploit unexpected situations as they arise, returning to sustain the primary mission effect once these interruptions are resolved. The methods presented enable the commander to recover quickly from these task deviations.

The remainder of the paper is structured as follows: Section 2 presents a view on the C2-WarpPlan Agent Architecture, indicating how the work presented here fits into a broader networked command and control structure. WarpPlan presents a rather more deliberative approach to earlier work in action choice determination for agents [2], [3]. Section 3 considers issues of information fusion relating to networked information sharing, taking into account commander preferences and task requirements to create the threat map. Section 4 discusses route planning within the threat map context. Algorithms derived from wave propagation through anisotropic ground media in seismology [4], [5], [6] are adopted and adapted with long-established, provably optimal, algorithms [7], [8], [9] to cater for obstacles and high levels of threat anisotropy. Section 5 considers three separate facets of operation: 1)

[1] www.mak.com and www.onesaf.net, respectively.
[2] HiLOCA (High Level Operations using Cellular Automata) is QinetiQ's command and control modelling and evaluation suite.

[3] Clearly, the freedom for personal expression afforded to individual commanders will vary considerably according to circumstances and command structure traditions.

the role and effect of commander preference in planning, 2) cooperative planning between commanders, and 3) analysis possible actions by an opposing force. Section 6 reviews some related uses of information fusion and planning in anisotropic spaces. Section 7 offers some concluding remarks.

2 The C2-WarpPlan Architecture

Figure 1 summarises relevant aspects of the C2-WarpPlan architecture and highlights several assumptions implicit in this paper. First, that the commander is part of a larger command chain. The central oval represents the scope of the individual commander, and aspects of the superior and sub-ordinate chain are also represented by ovals (figure 1, diagonal top-left to bottom-right).

Second, that the command troop will act as a largely self-contained unit, typically planning its activities on receipt of commands that express the superior commander's intent, and carrying them out as part of a larger strategic activity. Intent will be typically expressed at a high-level, often an order to achieve some *effect* on opposing forces, which must be translated by the troop commander into a Course of Action (CoA) and the detailed troop movements to be performed by the force in order to achieve the required effect. Such planning is a multi-faceted activity. This paper is primarily concerned with the analysis and presentation of perceived threat and route planning to pre-determined locations – the *effects target*. Other aspects of the operational planning process are considered here only in support of this.

Third, that the force will be operating in a Network Enabled Capable (NEC) Environment, represented in figure 1 as a "cloud" to the left, giving access to updated ISTAR (Intelligence, Surveillance, Target Acquisition and Reconnaissance) and in the context of IPB (Information Preparation of the Battlefield) information streams. It will be assumed that the commander is part of this network-enabled environment, and will continually receive relevant and frequently updated information about the position and disposition of various threats and hazards. Equally, the network capability will be used to pass intelligence back from individual field commanders to the "headquarters" function for analysis and redistribution to all – after analysis and interpretation. These threats and hazards are incorporated into a single threat map, which provides a clear and augmented visualisation of the Order of Battle (Orbat) disposition for friendly and opposing forces.

Fourth, it will be taken as axiomatic that the individual commander will take a personal view as to the relevance of the threats and hazards, and will tailor the significance rating of each element in the threat map according to their experience, current task and personality traits. Lastly, it will be assumed that the troop will have access to current electronic mapping and know where it is located (i.e. be GPS equipped, no doubt backed by conventional map reading skills).

The output of the WarpPlan process is a *direction vector field* over the area of the map, from which a preferred *vector route* can be prepared from the current (or indeed, any) valid location to the designated target. This vector route balances exposure to hazard with terrain traversal, according to the significance ratings given by the individual commander. Hazard is endemic in these actions, and can often only be reduced to the level acceptable by the commander at the expense of other mission parameters. Some will accept will accept a low-level of risk ("cautious"), some a balanced level, and some a high-level ("adventurous"). This variation is considered in section 5.1. Once the planned vector route is formed, other aspects of the planning process, such as determination of resource requirements and expected timings (the "*sync matrix*"[4]) can also be formulated.

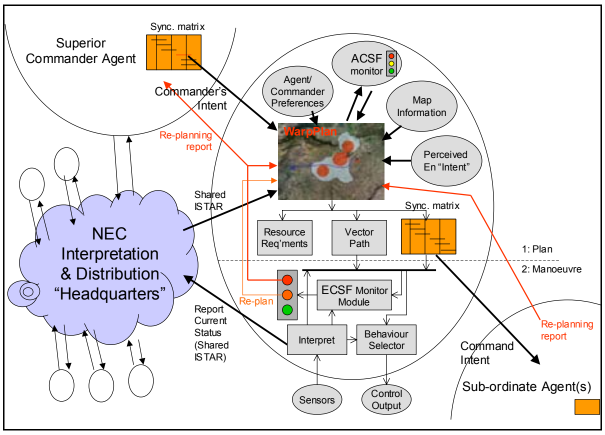

Figure 1: A view of the C2-WarpPlan Architecture

It will not, however, be assumed that, once created, the threat map and so the direction vector field will remain unchanging, or that a plan, once formed will be static, but that they must be changed as circumstances unfold. The threat map will be updated frequently and the vector direction field must be recomputed accordingly. Significant changes to the agreed plans need to be reported. It is also the case that several vector fields can be computed in advance of need, each based on the same threat map fusion assessment, but each reflecting a different anticipated, or contingent, phase of the operation: transit, move to cover, approach, secure, destroy or withdraw, for example, with different significance ratings and target locations being used for each alternative.

Equally, the vector routes created by WarpPlan represent an *a-priori* assessment of the situation. It is expected that the force commander will take immediate action to overcome local difficulties and take advantage of local circumstances, for instance, the opportunistic harassment of opponents and return fire or seek cover if attacked. These may necessarily take the troop away from the planned route but reference to the current direction vector field ensures the main mission may be resumed directly. Issues such as troop or squadron formation will also be decided according to local circumstances.

We specify the use of *Effects Critical Success Factors*[5] (ECSF, Louvieris *et al*, [10]) in the C2-WarpPlan

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[4] The sync matrix is rather in the style of a Gantt chart, indicating relative timings of coordinated activities.

[5] ECSFs are a development of the Surrey Defence Technology Centre at the University of Surrey.

architecture to monitor overall progress of the planned manoeuvre from initiation to completion. ECSFs are built on a Bayesian representation of Military Subject Matter Expert (SME) assessments of mission status – often based on such parameters as relative firepower advantage and the balance of combat losses. ECSFs provide a clear "green", "amber" or "red" indication of mission status. The "traffic light" display gives the commander an unambiguous indication of "achieved", "at-risk" and "not-achieved" for the current effect task. C2-WarpPlan interprets these as "OK to continue", "continue with additional caution" and "shift behaviour", respectively. Behaviour change might involve changing to a different (possibly pre-computed) direction vector field and associated ECSF criteria. It will almost certainly require that the change be notified along the command chain, as it will invariably have substantive implications for the broader mission.

3 Information fusion: the threat map

The Threat Map provides the commander with a single value indicating the threat prevailing at any particular location within the selected geographical map space, from *that commander's viewpoint*. Each commander will bring a different perspective to the interpretation of that threat. In part by role ("cap badge") – the commander of a well-protected armoured force will necessarily view threats and opportunities differently from the commander of a less well-protected infantry group, or a reconnaissance party, or a supply operation, due in part to current mission requirements and in part to the commander's own perception of the balance between the need to achieve the required effect and maintain the reasonable well-being of the force in his charge.

3.1 Threat types

We construct a threat map as an accumulation of each of many hazard types that are relevant to the commander, moderated by the actual or perceived severity of each threat type in the current context faced by the commander. Significant threat types may be broadly characterised into the following classes: a) physical obstruction and impassable areas, b) areas under prohibition or command constraint, c) cartographical features, natural and manmade, d) threats presented by opposing or hostile forces and e) safe havens and support available from own or friendly forces.

Figure 2 shows a hypsometric (blue-cyan-green-yellow-orange-red, low to high threat elevation) representation of the threat map within the context of the threat-profiling tool. The sliders to the left allow the commander to set personal preferences for the threat scaling for each of the threat types identified as significant for the effect or task being pursued. The buttons to the right establish reasonable defaults for various common effects, which may then be personalised. Selection of an effect type can also select the relevant slider set and activate the appropriate set of ECSF rules for effect monitoring.

Impassable areas, (a), are shown as white, and include significant expanses of water, but will include, for an armoured troop, cliffs, manmade obstructions and the like. Prohibited areas, (b), are nominally to be treated as impassable and may be established to allow proper coordination of resources or so as to not interfere with parallel operations. The fact that a commander might risk incursion into prohibited areas distinguishes them from true obstacles.

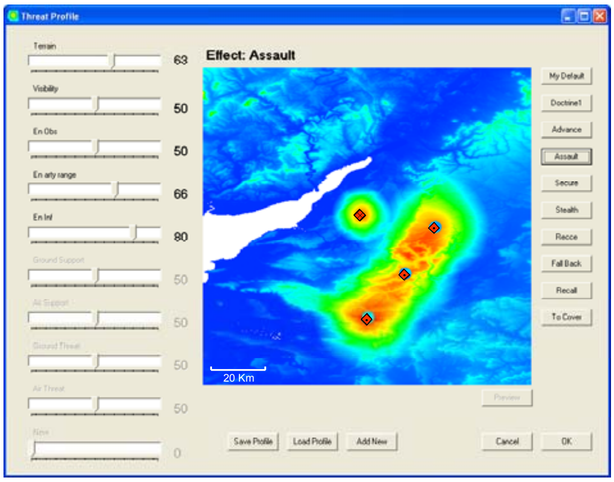


Figure 2: Threat map and profiling tool

The availability of digital cartography, (c), enables automated analysis of a wide range of mapped features, and their subsequent classification as hazard type. Of significance are natural features such as rivers and standing water, forests and the like, manmade features, such as urban conurbation and the transport infrastructure, road and rail. The universal availability of Digital Elevation Data represents a strong adjunct to conventional cartographic detail, and facilitates the computation of a variety of visibility constraints (e.g. [11]). The examples in this paper utilise a 3 arc-second grid-based mapping (1201^2 points, approx. 90 m, 108 Km^2), based on the Shuttle Radar Topography Mission[6] (SRTM) digital elevation data set. Some areas, notably cities and areas used for military training, have been measured to far higher levels of resolution (see, e.g., [12]).

Of most obvious significance, explicit threats, (d) and supports (e), are made available through a variety of conventional intelligence gathering activities: monitoring, tracking, reconnaissance and Unmanned Ariel Vehicle (UAV) activity, the sharing of observations between cooperating forces, and the use of locally sourced information.

By convention, friendly and opposing forces are indicated on maps using the App-6a (Mil Std 2525) map marking symbols[7], for instance, infantry: "⊠", "◈", armour: "▭", "⟐", artillery: "⊡", "⟐", reconnaissance: "◫", "◇", and anti-tank: "⍓", "◇". Rectangles represent friendly ("blue") and diamonds hostile ("red") forces. Note in figure 2 that the hazards represented by the marking symbols give rise to geographically diverse threat profiles (for instance, artillery "⟐" has a minimum and

[6] http://www2.jpl.nasa.gov/srtm/
[7] e.g. www.mapsymbs.com

maximum range and observers "◇" are limited by lines of sight). Not all threats are fully localised in this way and these threat types are reasonably represented by an elevation of the general threat level over a broader geographical area (e.g. air cover or covert forces known to be operating in the locality).

Implicit or inferred threat must also be considered (e.g. [13]). For instance, an area of the map may show a low overall threat value, but contrived deliberately so on the part of the opposing forces, in that it invites a force to enter that area with the specific purpose of canalising or entrapping it. Such inferred threats must be added to the visualisation, as they are determined. Not all threats can be directly represented geographically, for instance, the risk of being deceived or outmanoeuvred, and these must be considered separately in the overall planning process.

3.2 Representing threat types

We designate each specific threat or hazard type as an element, i (of the total, n), of the hazard vector $\boldsymbol{h}$. Each threat type will be represented by zero, one or more instances of the threat, each within the operational map area. So, for instance, there may be many opposing artillery positions, and these will be represented by one threat element. Threats are considered as positive values, supporting or mitigating circumstances negative[8].

Different artillery types may be given a separate threat type and be treated independently, if so required. Each element of $\boldsymbol{h}$ will apply to all individual threats and hazards of that type currently recorded on the map and will be applied uniformly. Future versions of the software may also allow for individual threats of a given type to be singled out for specific attention.

Note also the use of *perverse planning*, in which threats are deliberately underestimated, or treated as negative values, specifically with the purpose of acting in an unexpected way, against doctrine, to achieve surprise or to outmanoeuvre an opponent.

3.3 Threat significance elements

Each type element of $\boldsymbol{h}$ is matched by an equivalent moderating (weighting) element of the significance vector $\boldsymbol{s}$. Elements of $\boldsymbol{s}$ therefore express the commander's personal preferences and willingness to expose his forces to types of hazard and the dangers they represent in pursuit of his ends under the prevailing circumstances. Significant moderating factors include: a) The relative vulnerability of the commander and his forces to the threat type, b) the nature of the mission and effect or outcome required of the commander, c) the commander's personal view of the severity of the threat and the potential consequences of engaging with it, and d) the reliability the commander places on the source of the information. Of course, we do not expect the field commander in the field to consider each of these factors in detail separately, but to make a rapid single estimation based on experience and task.

This paper assumes an additive approach to threat. The *hazard level*, *hl*, at any given longitude/latitude (x, y) location on the map is indicated by:

$$hl_{x,y} = \sum_{i=0}^{n} (\boldsymbol{h}_{i,x,y}\, \boldsymbol{s}_i),\ \forall x, y \tag{1}$$

While appreciating that the threat surface is necessarily continuous, we take a finite element approach, and calculate the threat at a finite number of locations over the map area (conveniently, though not necessarily, on a grid). Individual hazard values at these locations are calculated or interpolated as required. The distance between grid points will be designated by d (d = ~90 m for the SRTM data used). As threat cannot reasonably be interpreted as less than zero, it is rescaled to provide an expected *hazard value*, *hv*, for each discrete x, y location:

$$hv_{x,y} = r_{x,y} + k \frac{hl_{x,y}}{\max(hl) - \min(hl)},\ \forall x,y \tag{2}$$

Expected threat is not equivalent to actual threat, as threat factors may not have been adequately detected or anticipated, and an appropriate level of situational awareness and vigilance is required at all times. The threat map does, however, directly indicate the level and type(s) of known threats. The rate value $r_{x,y}$ represents the cost of physically traversing the region at x, y. At a minimum it equates to the best estimate of transit time that may be achieved at that location and is terrain dependent. As $r_{x,y} > 0$ (by definition), it places a lower bound on the value of *hv*. Constant k scales the threat component.

The current implementation only requires the commander to make one value judgement per hazard type, a single slider control setting each hazard type relative to the others. The scale is arbitrary (0-100%), as substantive problems arise with attempts to provide a consistent calibration scheme across such a heterogeneous range of factors. Personal settings for various situations can be considered ahead of time, saved and recalled when needed (figure 2, bottom).

It is not our intention here to stipulate how the moderating factors for the individual commander are to be combined for vector elements in $\boldsymbol{s}$. However, many situations arise on a regular basis in which a standardised view of each threat type is required. Such "doctrinal" settings are appropriately developed using established group consensus and experience capturing techniques such as Delphi methods [14], the Analytic Hierarchy Process (AHP), [15], [16], or utility analysis.

4 Planning in the threat map space

In this section we consider how the hazard map may be converted to a navigational vector space. This vector space may then be used to directly form routes through the threat space indicated by the hazard map. We assume that the current (starting) location of the troop is known, and that the desired end location of the troop has also been established. The vector space then provides a new

[8] Note also that the examples used here are strictly for illustration only and are not intended give a true representation of military threat or its interpretation.

instantaneous indication of direction along this preferred route. If all goes to plan, the original route is followed to the target. If the troop is obliged by localised circumstances to deviate from this route, the vector space always indicates the direction of the (new) preferred route from the new, changed, location once the primary mission may be recommenced.

The computed preferred route is entirely dependent on the validity of the current hazard map, its associated significance weightings and the target location. If these change, the "preferred" route will be invalidated, and the hazard map and vector space must both be recomputed. The preferred route is expressed as a list of contiguous (longitude/latitude) coordinates interpolated through the grid, spaced by some small increment ε, typically some fraction of the grid distance d. Construction of the route is described later. The preferred route may be used to provide an estimate of the total distance to the target, time to target and cumulative hazard expected.

Construction of the vector space from the hazard map proceeds in two stages, first as a propagation process to characterise every grid location in terms of the shortest preferred route to the target location, followed by a calculation of the rate of change of the propagation field at each grid location to determine the travel angle of the route back to the target at that point. The treatment here assumes a wavefront starting at the target location and travelling outwards towards the edges of the defined operational area at a rate inversely proportional to the hazard values (hv) encountered. The wavefront travels rapidly in areas of low hazard and slowly in areas of high hazard. This method has been used extensively in seismology to compute first arrival times of shockwaves travelling through anisotropic substrates.

4.1 Wave propagation

The approach used in the implementation (eqns. 3-7) is as presented by Vidale [4]. It is included here for completeness, with some minor notational changes. Comprehensive treatments of the general problem may be found in, for example, [6], [17], [18].

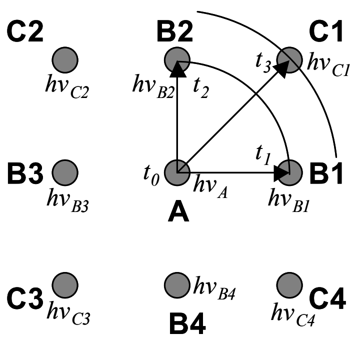


Figure 3: Wave propagation process

Consider the elements of the grid (figure 3, adapted from [4]), with a source of perturbation at point A and a hazard value (hv_x) at each of the nine points. The distance between grid points is d and we require the propagation time (t_x) from A (currently t_0) to any other point B1-B4, C1-C4 not yet visited. Next, we specifically consider the incremental propagation rates to B1 (t_1), B2 (t_2) and C1(t_3); remaining points are treated equivalently. The propagation of the wavefront from each source point (including the initiating target point) is described by the eikonal ray tracing equation:

$$\left(\frac{\delta t}{\delta x}\right)^2 + \left(\frac{\delta t}{\delta y}\right)^2 = hv^2(x, y) \tag{3}$$

Equations 4 and 5 approximate the differential terms as finite differences:

$$\left(\frac{\delta t}{\delta x}\right) = \frac{1}{2d}\,(t_0 + t_2 - t_1 - t_3) \tag{4}$$

$$\left(\frac{\delta t}{\delta y}\right) = \frac{1}{2d}\,(t_0 + t_1 - t_2 - t_3) \tag{5}$$

where:

$$t_1 = (hv_{B1} + hv_A)\,d\,/\,2;\ t_2 = (hv_{B2} + hv_A)\,d\,/\,2 \tag{6a, b}$$

and so:

$$t_3 = \sqrt{2(hv_{C1}.d)^2 - (t_2 - t_1)^2} \tag{7}$$

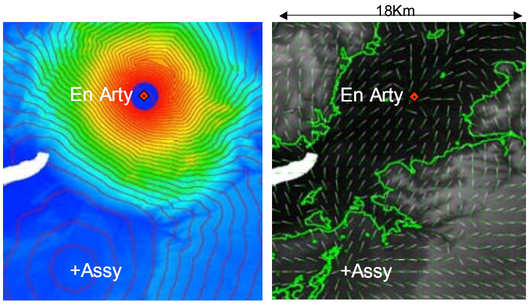
Vidale proposed the use of an "expanding-box" algorithm, growing the wavefront in a spiral form from the initiating source. While efficient in implementation, this approach limits the degree of hazard anisotropy and does not adequately cater for propagation voids in the medium [19], such as those caused by obstructions and prohibited areas.

To overcome these issues, the grid is treated as a weighted (by $hv_{x,y}$) 8-connected graph; node expansion then follows the uniform-cost search (UCS) model (e.g. [7]), a variant of the well-established and commonly adopted A* algorithm ([8]; note also Dijkstra, [9]). In this implementation nodes for expansion are maintained in an ordered list, the current least accumulated value node being expanded. Expansion starts at the target node, and is complete when the list is empty. Discovery of a shorter trail re-starts expansion from that node. Nodes in obstruction and prohibited areas are excluded from expansion and are not considered, as they are unreachable. Note that if $k = 0$ (eqn. 2), routes generated are equivalent to shortest time paths avoiding obstacles, and if r is also made constant then shortest distance routes are formed.

The UCS model adds a significant computational overhead compared to the expanding box method, but the search is complete, in that it visits all reachable nodes and optimal, in that the final values at each grid node represent the minimal total en-route hazard value sum to the target. As $hv_{x,y}$ (eqn. 2) is positive (> 0), each node is guaranteed to be larger than its predecessor in any wave expansion trail, avoiding the formation of local minima. On completion, at least one minimum route is defined from every reachable node on the map to a target node.

At a minimum, every reachable node must be visited at least once during the UCS process. Re-expansion of nodes can potentially add substantially to the computation time. In practice, this is not observed, the re-visited nodes remaining a small proportion (~30%) of the total. For the 1201x1201 map areas used (max. 1442401 reachable nodes), the mean time required to compute the wave propagation was reported as 15.45 seconds ($n = 10$, std. dev. = 0.55, Pentium 3.2GHz HT processor) for the examples used. Note that this method may also be extended to 3D spaces (e.g. [5]), and so may find further application in sub-marine or aviation environments.

As a convenient side effect of the UCS algorithm, nodes represented in the expansion list may be highlighted on the map to provide an immediate visualisation of the expanding wavefront or retained as contour lines showing the order and rate of expansion across the map surface. Figure 4 (left) shows the effect of an area of high hazard (note the contour lines shown at reduced intervals in high-hazard, low propagation rate areas).



Eikonal propagation contours Recovered direction vectors

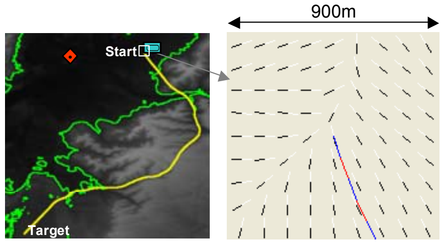
Figure 4: Propagation contours and direction vectors

Note also that the UCS algorithm permits several grid locations to be nominated as target locations simultaneously, propagation waves starting from each independently until they meet and merge. There is then a preferred hazard route to at least one of the targets from each reachable node. This is useful, for instance, when an exposed troop must be aware of multiple "safe" locations to which it might retreat in the event of an attack, or where there are several equally valuable targets, any of which might be attacked as the opportunity arises.

An approximation to the preferred hazard route from any reachable node to a target may be created by simply following the lowest value node from the eight neighbours of the current route node, and repeating this until a target node is reached. This approach is commonly adopted in route planning simulations and is guaranteed to find a valid route where one exists. However, there are several disadvantages to this scheme. The routes produced by this method significantly over-estimate the true distance, as the route is composed of edges and diagonals (an augmented Manhattan distance, d and $d\sqrt{2}$). The method also gives rise to unattractive routes composed of straight-line segments, which fail to adequately reflect the texture of the threat landscape. The next section describes a refinement of the scheme to provide a continuous interpretation of the route.

4.2 The vector field and vector routes

In the second stage of the planning process the slope in x and y of each reachable location node on the propagation map is calculated and represented as a direction vector. These vectors indicate the direction of travel along the preferred route to the nominated target for each non-target and reachable node. Figure 4 (right) shows a sample of these vectors over a broad area and are illustrated in detail in figure 5 (right, local vector view). Figure 5 (left, elevation view, the 50m elevation contour line is also shown) shows the overall preferred route given the artillery hazard indicated.



Overall preferred path (41.1Km) Instantaneous navigation vector (167°)

Figure 5: Overall route (left), local vector field (detail)

Equation 8 describes an interpolation scheme that gives a continuous valued direction vector at every location within close proximity of a reachable node. Consider any place Q (edge inclusive) within the bounding box of four adjacent nodes in the map grid, A, B, C and E, each with a computed direction vector $\boldsymbol{a}$, $\boldsymbol{b}$, $\boldsymbol{c}$ and $\boldsymbol{e}$, respectively and each with a scalar distance d_x from Q. The resultant direction vector $\boldsymbol{q}$ is the vector addition of each of the neighbouring node vectors scaled by the distance of the actual location to the node.

$$\boldsymbol{q} = (d - d_a)\boldsymbol{a} + (d - d_b)\boldsymbol{b} + (d - d_c)\boldsymbol{c} + (d - d_e)\boldsymbol{e}$$
$$\text{where if } d_x > d, \text{ then } d_x = d \qquad (8)$$

Now, by choosing a small movement step size ε, $\varepsilon < d$, and following the angle (the magnitude component is discarded) indicated by $\boldsymbol{q}$ at each step, a substantially better approximation to the preferred route may be obtained. The first five steps in this route (from the central node, $\varepsilon = 50$ m) are shown in figure 5 (right). Note that this route may start at any valid location in the map area, and intermediate steps are similarly placed. The route is computed rapidly, and the user may place the mouse pointer at any place on the map and receive an effectively instantaneous indication of the immediate direction vector, the cumulative distance to target and see the route drawn.

5 Illustrations of operation

This section illustrates some of the modes of operation available in the C2-WarpPlan Architecture. In the first instance we consider the effect of commander preference in calculating an approach to a direct assault scenario. In the second, we consider shared planning between cooperating commanders. In the third, we briefly consider the use of C2-WarpPlan to analyse possible and likely approaches by a hostile force on a presumed (blue) target location.

5.1 Effect of commander preference

Figure 6 (threat view) illustrates the effect of differing commander preference settings when planning an "assault" on a target location at the centre of the map, ostensibly protected by several defensive batteries. A cautious troop commander (left map) perceives the defences as essentially impenetrable, and will take a far less direct route (108 Km upper, 107 Km lower) than the less risk adverse one (right map), who decides (perversely, perhaps) that the shorter (64/66 Km) routes through the defences are appropriate. Note that in both cases the attacking troop must enter the high hazard area about the target location to complete their respective missions.

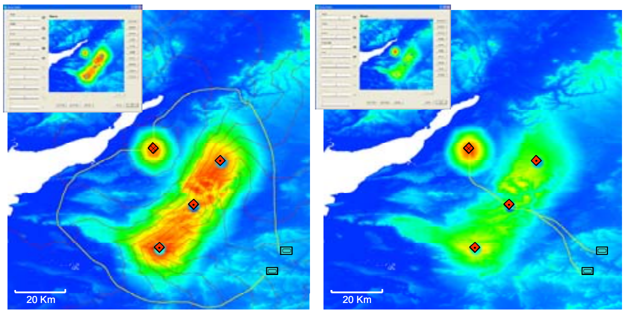


Figure 6: Effect of commander preference

5.2 Cooperative planning

Figure 7 (in elevation view) illustrates inter-troop coordination, in which cooperating blue forces, TpA – TpF, mount a concerted assault on red forces En1 and En2. Each calculates a proposed route according to their role, task and preferences. These are then communicated over the network infrastructure to their superiors and, if appropriate, to each other. It may be seen that the routes proposed by troops C, D and E share a final approach phase (circled), indicating the possibility of congestion or vulnerability to hastily formed defences. If this is determined to be a significant problem, routes may be recomputed with alternative preference parameterisations.

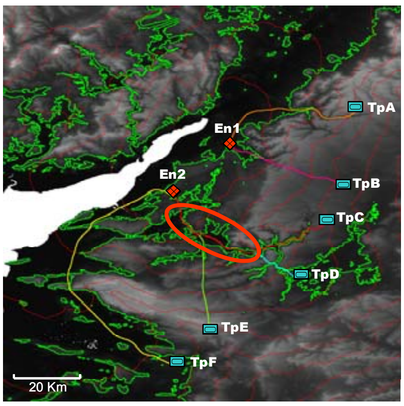


Figure 7: Multi-troop cooperative planning

5.3 Analysing enemy intent

Figure 8 illustrates an approach to analysis of opponent intent. Predicated on the assumption that red forces have an identified blue target and that they may be located in any direction, an approach profile may be formed and avenues of current vulnerability identified, countered and reanalysed. The analyst must further consider the range of preference options available to the opponent, re-running the analysis for a range of probable and possible profile settings, based on known or assumed red commander behaviour and doctrine, such analyses being superimposed for a more complete picture of the threat presented, the possibility of red perverse planning being a significant consideration here. The actual positions of red forces may be known, reducing the need for 360º analysis as shown below. Application of the tool for both blue and red forces in this manner enables a more complete simulation of the battle space as the operation proceeds, with the actions of both forces being considered repeatedly in response to each other over an extended period.

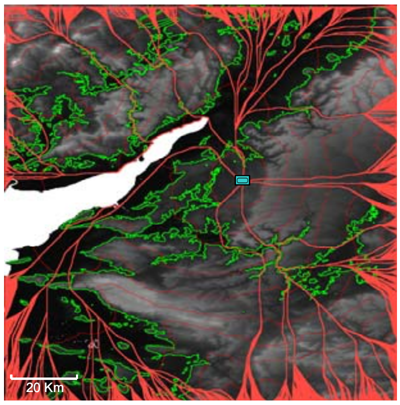


Figure 8: Analysing possible enemy approaches

6 Related work

The notion of the threat map and route planning presented here has close parallels with that of an "accumulated cost surface" [20], used for land suitability analysis in GIS (Geographical Information Systems) applications. For instance, archaeologist Meghan Howey [21] has hypothesised about land usage by past populations based on existing surface properties. Ganskopp *et al* [22] considered the effects of least effort pathways in livestock trails, largely based on the degree of slope and the resultant energy requirements to traverse any given area. Delvar and Naghibi [23] have applied cost surface methods to oil pipeline routing, taking into account diverse – and often competing – geological constraints, cost and population factors. Similarly, Berry [16] reports on a cost-surface based analysis for routing power cables, taking into account a weighted consensus of different stakeholder perspectives (residents, legislators, environmentalists, engineers, etc.) Related methods have been proposed for robot and autonomous vehicle path planning (e.g. [24]) and tactical path planning [25], [26].

7 Summary and further work

We have presented an information fusion approach to high-level tactical information to create a threat map, with both a clear visualisation and that acts as input to a route planning mechanism in the context of our C2-WarpPlan Agent Architecture. The methodology takes account of the role and effects currently assigned to a commander and balance of these with the individual commander's experience and preferences. We illustrate the methodology with several possible modes of operation.

We consider several refinements and further applications of this work to be noteworthy. First, to establish a set of default ("doctrinal") settings for each of the effects modes already identified (section 3.3) using serving commanders and various Subject Matter Experts (SMEs), and to identify the extent and range of variability that might be expected for each effect type. Second, to evaluate these settings in the context of several tactical vignettes (such as "assault", "secure" and "destroy" effects) that have already been established in the context of land warfare expertise. Third, we wish to investigate analytic methodologies to determine the optimal hazard settings when an overall time to completion for the mission is regarded as the paramount parameter. Fourth, to use the methodology described here at several levels of resolution, reflecting a commander's multiple concerns to balance the overall mission parameters with the need to act appropriately in the light of immediate surroundings, opportunities and threats. Finally, we intend to consider the role of secure network data communications to ensure safe and reliable information sharing and fusion.

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