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A Flexible Toolkit Supporting Knowledge-based Tactical Planning for Ground Forces

Topic(s)

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Abstract. *This paper presents the prototype framework C2DSAS (Command and Control Decision Support and Advisory Services) which has been developed for the Austrian Armed Forces to explore software-aided estimates of the situation and tactical planning support for ground forces. The goal of C2DSAS is to provide a toolkit which can be flexibly applied to various planning and re-planning tasks in particular for troop movement and engagement. The fundamental design principle is to support tactical planning tasks by methods from artificial intelligence in order to speed up the estimate of the situation in various scenarios while keeping humans as the driving element for decisions. On the basis of 2D/3D digital terrain representation, a set of operational rules, the current situational picture, as well as the capabilities and characteristics of individual vehicles, weapon systems or whole organizational units, the C2DSAS toolkit facilitates the generation of optimal and alternative paths depending on various optimization functions such as time, distance, or engagement opportunities. It enables the determination of discrete paths, troop spreading models, manoeuvrability, visibility, and zones of fire in a fully generic way and therefore constitutes a valuable tool set for supporting tactical/operational decision making for military purposes as well as in the context of crisis management and disaster relief.*

1. Introduction

In complex tactical situations commanders are often forced to take decisions within a very short time frame. Factors, such as enemy, environment, own forces have to be evaluated simultaneously. Modelling different tactical scenarios and frequent re-planning based on accurate and timely information in a highly dynamic mission environment can improve decision quality.

Currently fielded command and control information systems provide decision support capabilities basically by improving situation awareness. Huge amounts of data are exposed to commanders and staff personnel and sophisticated data distribution mechanisms, filtering techniques, and optimised human-machine interfaces are utilised to create operationally valuable information from distributed data sources. However, the full potential for decision and planning support in complex tactical situations can only be tapped by significantly enhancing the level of data processing. Combining battlefield terrain information coded in the map with time-stamped and geo-referenced information on units and tactical control features (i.e. the operational picture), and augmenting it with a set of business rules and constraints, the following tasks should be supported:

- determination of optimal paths for own troops based on different optimization functions such as time, distance, or engagement opportunities
- troop movement projection including the determination of visibility and zones of fire
- modelling of anticipated enemy movement and determination of engagement areas
- identification of danger zones

From the variety of data available in a modern map-centric command and control information system, a multi-dimensional configuration space is to be built up. Known techniques from artificial intelligence and information theory can then be applied to facilitate the above listed tasks in order to improve the quality of tactical planning by automated battlefield terrain analysis while keeping humans as the driving force and last instance of decision making.

The research project C2DSAS (Command and Control Decision Support and Advisory Services) conducted in cooperation between University of Klagenfurt, the Austrian Ministry of Defence/Austrian Armed Forces and Frequentis AG aimed at

- the design of a suitable configuration space
- identification and analysis of existing processing techniques and algorithms with respect to functional suitability, robustness, and performance
- development of a proof-of-concept prototype setup

This paper presents the main outcomes of the project. The algorithms and approaches which were best suitable for the above mentioned tasks were implemented in the C2DSAS Toolkit which will be discussed in the following sections. It should be noted that little effort has been spent to visualize calculation results in the C2DSAS proof-of-concept-prototype as yet. All screenshots presented in this paper are for demonstration purposes only.

The remainder of the paper is structured as follows. In Section 2 an efficient approach to represent the digital map as well as operational rules is discussed. In Section 3 algorithms used for movement planning are presented. Section 4 addresses engagement planning algorithms which are used to realize the functionality of determining visibility zones, fire zones, assembly areas and battle positions. Section 5 presents the overall architecture of the resulting C2DSAS toolkit and furthermore discusses the prototype setup. Section 6 discusses the most relevant related work. Section 7 concludes the paper and gives a short outlook on future work.

2. Configuration Space and Operational Rules

In the C2DSAS toolkit the digital map is represented by a quad-tree data structure that is based on cell division [Samet 1990]. Each cell contains information about its position and spatial extent. Starting with cells of maximum size (e.g., only one big cell) that cover the total map area each of these cells are divided into four (therefore quad) smaller cells. This is repeated recursively until either the desired resolution or a predefined stopping condition is reached. Figure 1 shows an example of such a cell division and the corresponding quad-tree.

In the C2DSAS toolkit the resulting cells are of variable size as only cells which are inhomogeneous (i.e. cells which are subject to more than one cell type) are to be further divided until they become homogeneous (i.e. can be unambiguously classified) or reach a minimal cell size. Common cell types are "class 1 road", "building", "forest", or "lake". By further dividing inhomogeneous cells more and more cells become homogenous. The whole map is represented by the (not necessarily homogenous) leave nodes of the resulting quad-tree.

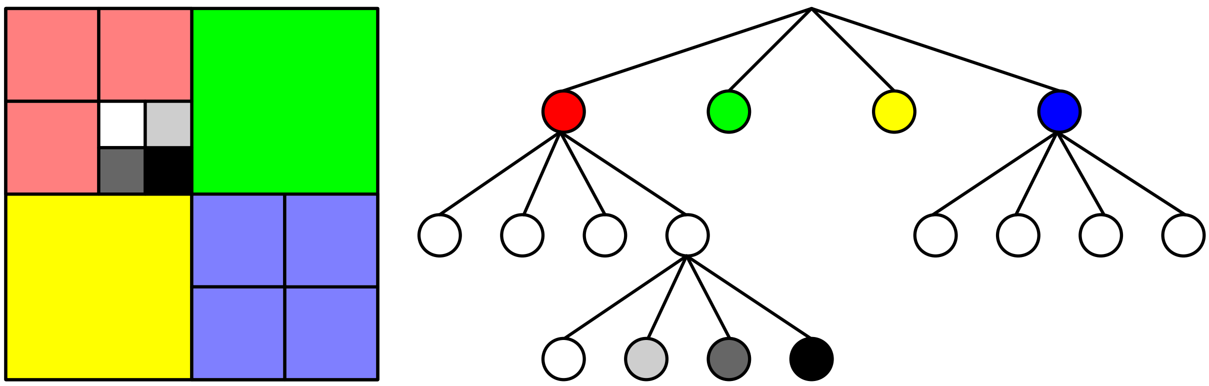

Figure 1: Principle of quad-tree approach. Beginning with cells of initial size (e.g. only one big cell) all resulting cells can be further divided.

Representing the map by a quad-tree structure decreases significantly its memory consumption which significantly accelerates further computation. Figure 2 shows an example of the cell computations and classifications by quad-tree in the C2DSAS toolkit. Once the cells have been computed, a search node graph can be built up incorporating the cells and their neighbour information.

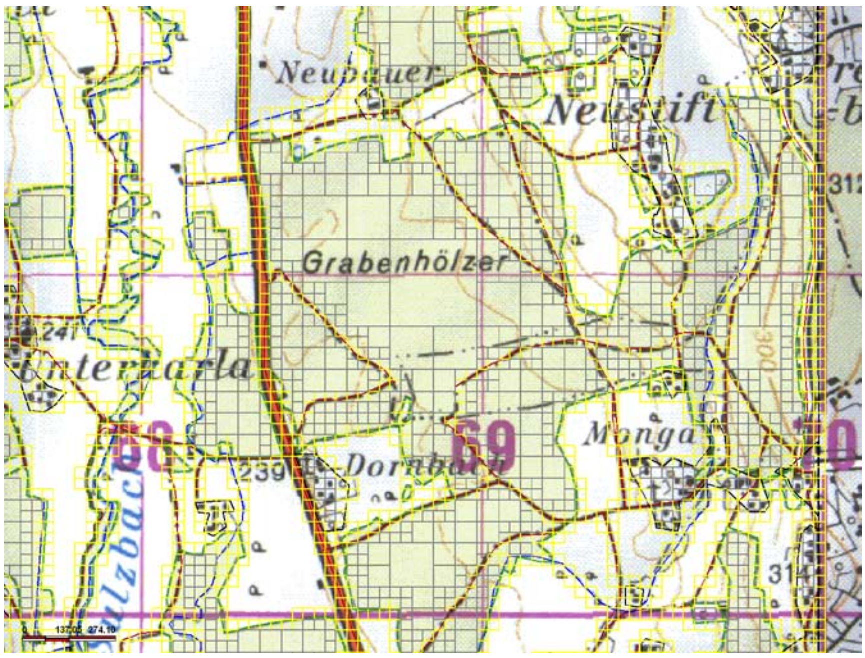

Figure 2: Quad-tree calculation in the C2DSAS toolkit. The map area is divided into geo referenced cells of different sizes. The cells are produced and stored by means of quad-trees.

In addition to geographical information knowledge about equipment characteristics, operational rules, and constraints are maintained in the C2DSAS toolkit. This rulebook which has been defined in cooperation with the Austrian Armed Forces contains information about organizational elements like troops or vehicles, their abilities on different terrains, and their minimum, average, and maximum speeds given different terrain types, and further conditions like day time or weather. The map representing cell structures and the resulting search graph together with the rulebook constitute the basis for all further computations.

3. Movement Planning

In the context of developing own “courses of action“, the commander has to evaluate the possibilities of own and enemy forces with respect to the factors “force”, “space” and “time”. A typical example is the calculation of one or more alternative (near-) optimal paths to mission targets. When a digital map representation in form of a cell/node-based tree structure is given, many different search algorithms can be applied in order to determine one or more alternative paths from a given start to a given end point. A well-established algorithm widely used in navigation systems, geo-information systems, or computer games, is the A* (speak ‘A Star’) algorithm [Hart et al. 1968]. A* is a search algorithm which can be seen as a heuristic extension to Dijkstra’s Shortest Path algorithm. Whereas Dijkstra’s Shortest Path algorithm always explores the node with the minimal path costs, A* calculates the estimated path cost to the goal node f(n) for every current node which could be explored and further extended, whereby node extension refers to the calculation of neighbour nodes (successors). A* extends the node with the minimal estimated path costs to the goal. The estimated path costs in a node f(n) is the sum of the prior path costs g(n) and a heuristically estimated distance to a goal node h(n), i.e.

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

When the heuristic part of A* is deactivated (e.g. by setting h(n) to a constant value), A* degenerates exactly to Dijkstra’s algorithm. The heuristic function h(n) is highly dependent on the search domain. In the context of path finding, the most widely used heuristic for map search problems is the airline distance to the target, such that nodes with a shorter airline distance to the goal are preferred by the algorithm. No limitation is imposed on the underlying cost function by which the optimality of a path is defined as long as there are no negative costs. In this case A* cannot guarantee to find the optimal solution. Examples for cost functions in this circumstance are distance (i.e. the shortest path is the optimal one) and time (i.e. the path which leads fastest to the target is the optimal one). Note that for calculating the fastest path the different average or maximum speeds of the different moving elements (e.g., soldier, AFV, MBT, ..) on different terrains (street type, water, forest, etc.) have to be considered (i.e. found in the rulebook) by the cost function, whereby a maximum speed of zero would mean that some specific terrain cannot be passed by the moving element.

In order to make path calculation flexible enough such that tactical commanders are able to use their knowledge and experience the C2DSAS toolkit (apart from the different cost functions) offers the following two possibilities of system manipulation:

- Definition of mid points, i.e. points where a path has to go through.
- Definition of Special Areas for which the movement costs are rather predefined than calculated by the cost function.

Using intermediate path points offers the possibility to direct path search and to produce a set of alternative paths including different intermediate points. Hereby an easy way of path comparison is provided to the commander.

Figure 3 shows a screenshot of path visualizations as calculated by the C2DSAS toolkit. Here, three alternative paths for one moving troop have been calculated in order to be compared. Intermediate points have been used in order to roughly direct the path calculations. This way it is also possible to concurrently calculate optimal paths for friendly and enemy forces in order to estimate the probability of contact. In Figure 4 a typical result is displayed. The question to be answered is whether it is possible to pass a certain point before an enemy force can reach it or not. In the example of Figure 4 there would exist a high probability of not passing this point (second yellow circle) in time, as the enemy force (red path) could reach this point in less time than the friendly forces (green path).

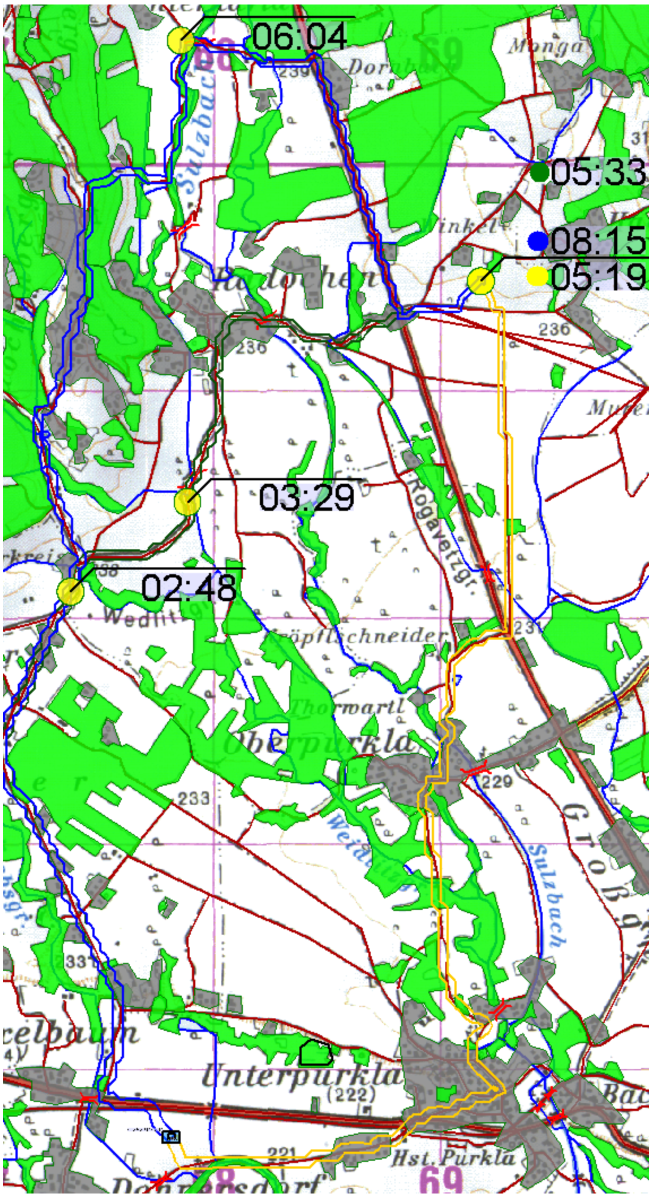

Figure 3: Path alternatives produced by means of intermediate points. The goal and the intermediate points for spanning the alternative routes are indicated by yellow circles including the respective arrival time. The yellow path is the quickest (arrival at 05:19). Although longer, the dark green alternative does not need much more time (arrival at 05:33). The blue alternative needs much more time.

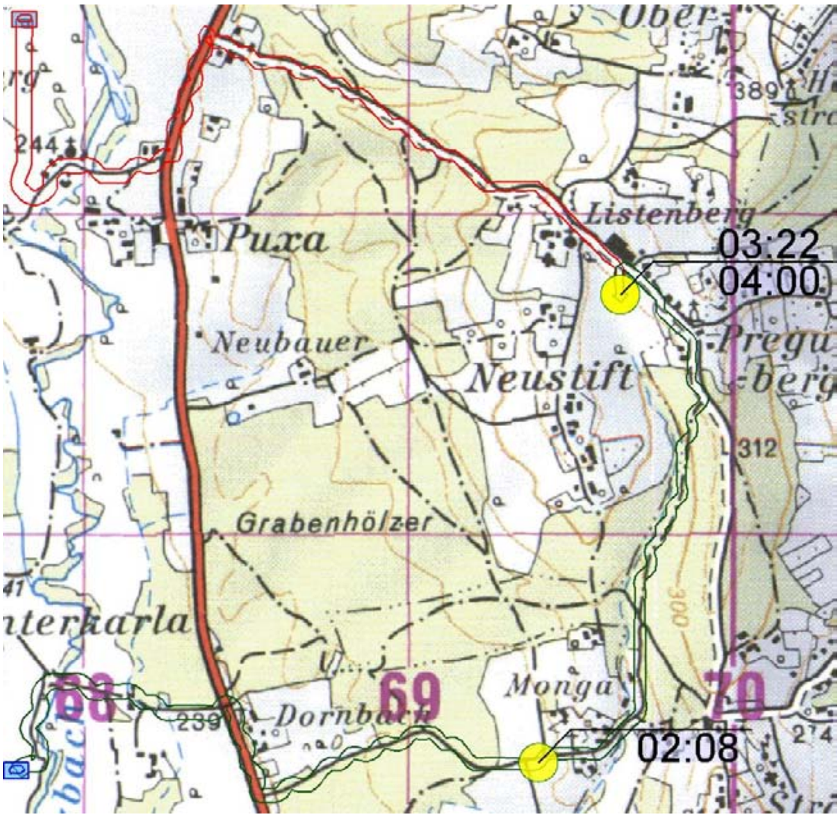

Figure 4: Alternative paths used to estimate probability of enemy contact. The green path (friendly forces, arrival at 04:00) needs slightly more time than the red path (enemy forces, arrival at 03:22).

The other important mechanism for directing path calculations are so called 'Special Areas' (SAs). An SA is a simple tool to model time-dependent obstacles in a quasi-static way. Its purpose is to indicate areas where movement is either obstructed or accelerated. SA can be parameterized to model:

- Inhibition (movement is slowed down e.g., due to enemy activity or adverse weather conditions)
- No-go (movement is impossible e.g., due to a destroyed bridge, or deliberately to be avoided)
- Acceleration (movement is accelerated or made possible, e.g., by means of a pontoon bridge)

In the C2DSAS toolkit, activation time-slots can be assigned to each of the Special Areas to model its temporal behaviour. In Figure 5 an optimal path going over two defined intermediate points is shown when it is not obstructed (top), inhibited by 50% (lower right), or impossible (lower left) during time slot 62-182. In the No-go case the first part of the calculated path is completely different when compared to the original path. Due to the limited activation time of the SA the path is eventually joining the original one.

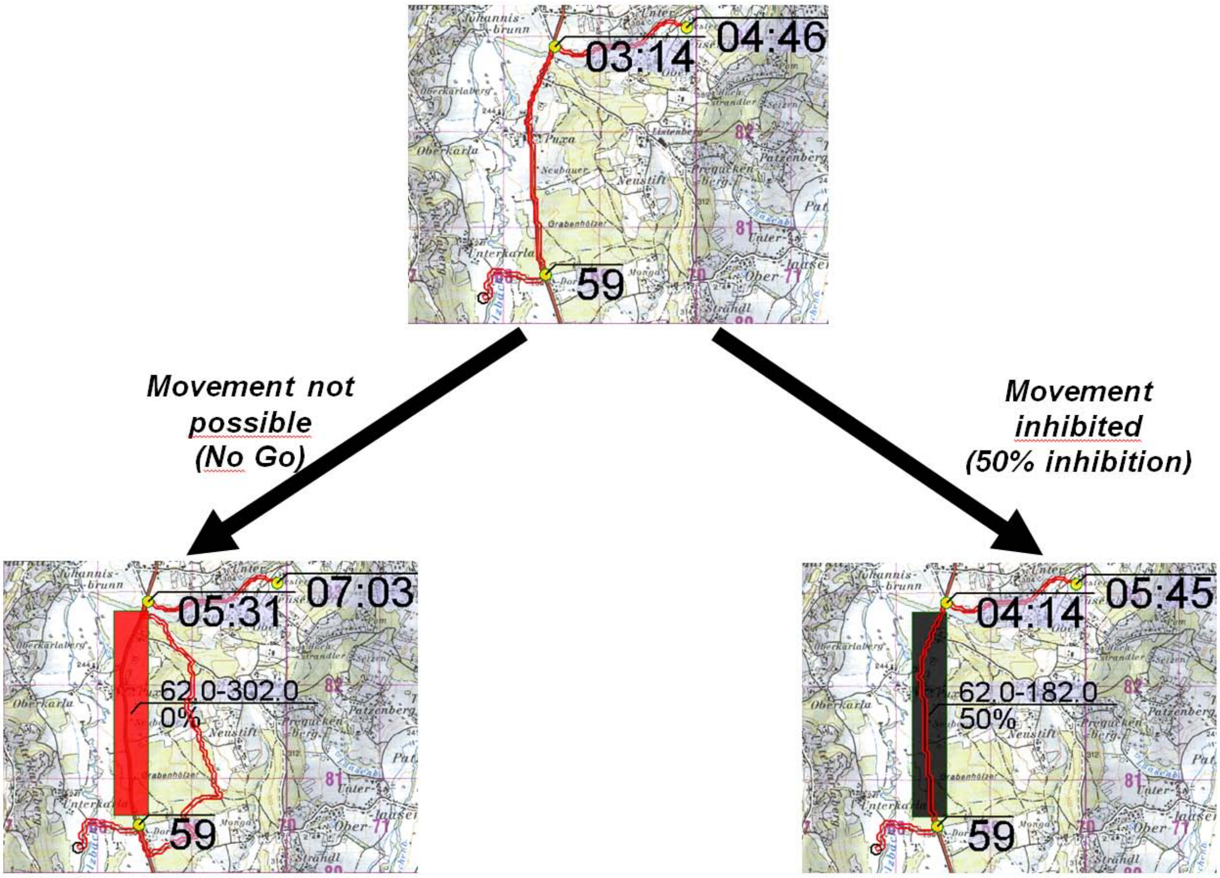

Figure 5: Inhibiting and No-go Special Areas. Strategic intermediate points and the goal including the arrival times are indicated by yellow circles. The Special Areas are indicated by red (No-go) and dark grey (inhibiting) zones. The grade of inhibition (e.g. 50%) is as well indicated as the time slot (e.g. 62.0-302.0) when the Special Area has to be considered and thus changes the resulting path (red).

The third type of SA type facilitates (accelerates or enables) movement. In Figure 6 an example is shown where a path has to cross a river. In the left picture an existing regular bridge has to be used. In case e.g., a pontoon bridge has been installed by own engineering troops, this fact can be taken into account by defining an appropriate SA (green rectangle on the right picture).

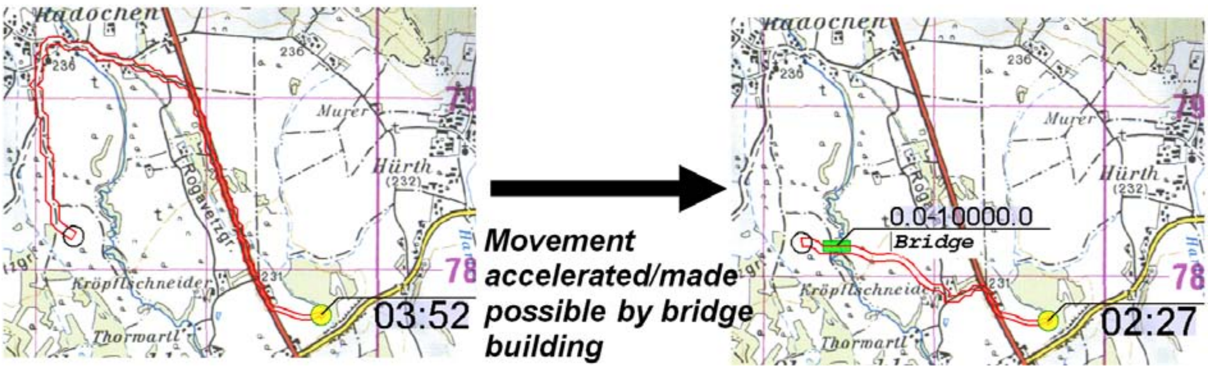

Figure 6: Accelerating Special Areas. The commander's knowledge about the existence of a pontoon bridge can be modeled by means of a Special Area (green). Thus, a much shorter path (red) can be found (arrival at 02:27).

Another important planning task which can be efficiently supported by the C2DSAS toolkit is the calculation and display of terrains which can be reached by forces in a given time period. Technically, the functionality for such movement projection models are already given by Dijkstra's Shortest Path algorithm (i.e. also A* with dummy heuristic). The principle is as easy as follows:

- Define a goal which cannot be reached in a certain time period. (For example by defining the most extreme possible point on a given map.)
- Start the search algorithm.
- Stop search algorithm when first node is expanded which has bigger path costs (i.e. time) than the predefined maximum.

All nodes (including cells) which have been expanded are reachable in the predefined time period. Figure 7 shows an example calculation of such a reachable area for a predefined vehicle (i.e. maximum speeds for different terrain types have been taken into account). The yellow cells indicate the cells which can be reached in a given time. The green cells indicate forest where the given vehicle is obviously not able to move, and the grey areas indicate zones where it is forbidden to move by predefinition (e.g. inner cities). Thus, by using functionality which is already given by the path calculation abilities the C2DSAS toolkit can also produce movement projection models for forces easily.

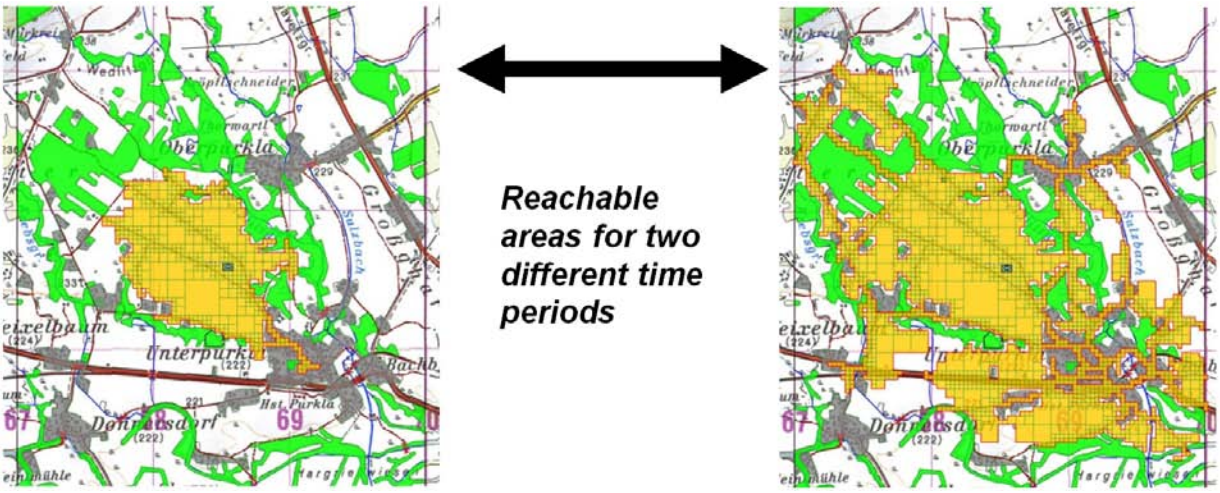

Figure 7: Movement projection models produced by the C2DSAS toolkit. Green cells (forest) and grey cells (inner city) represent areas where the example troop is not able or allowed to move. The yellow cells indicate the reachable areas.

4. Engagement Planning

Another class of planning steps which can be efficiently supported by the C2DSAS toolkit is the calculation of suitable battle positions for friendly forces of company size or bigger in a given area. These positions are determined by the reachability of the area and by achieving optimal effects when firing out of this area. The configuration space for such calculations is again based upon a digital map representation in form of tree structures and cell incorporating nodes, as well as the definition of so-called "dividing" terrain types that inhibit cooperation and coordination of own forces, i.e.

areas where it is not possible to line up adequately. Typical terrain types which are regarded as dividing are ‘water’ or ‘forest’. However, whether a certain terrain type qualifies as “dividing” depends on the respective type and size of the force. Figure 8 shows an example of identified dividing areas and derived favorable battle position areas (and centers) for an example troop of size 500m x 1000m. The basic procedure for doing the calculations is as follows:

- Identify dividing areas (i.e. water, forest, buildings, other obstacles)
- Enlarge dividing areas depending on the troop’s spatial requirements (e.g., company, battalion)
- Each cell/node not being part of an enlarged dividing area constitutes the centre of a corresponding favourable battle position for the respective troop size

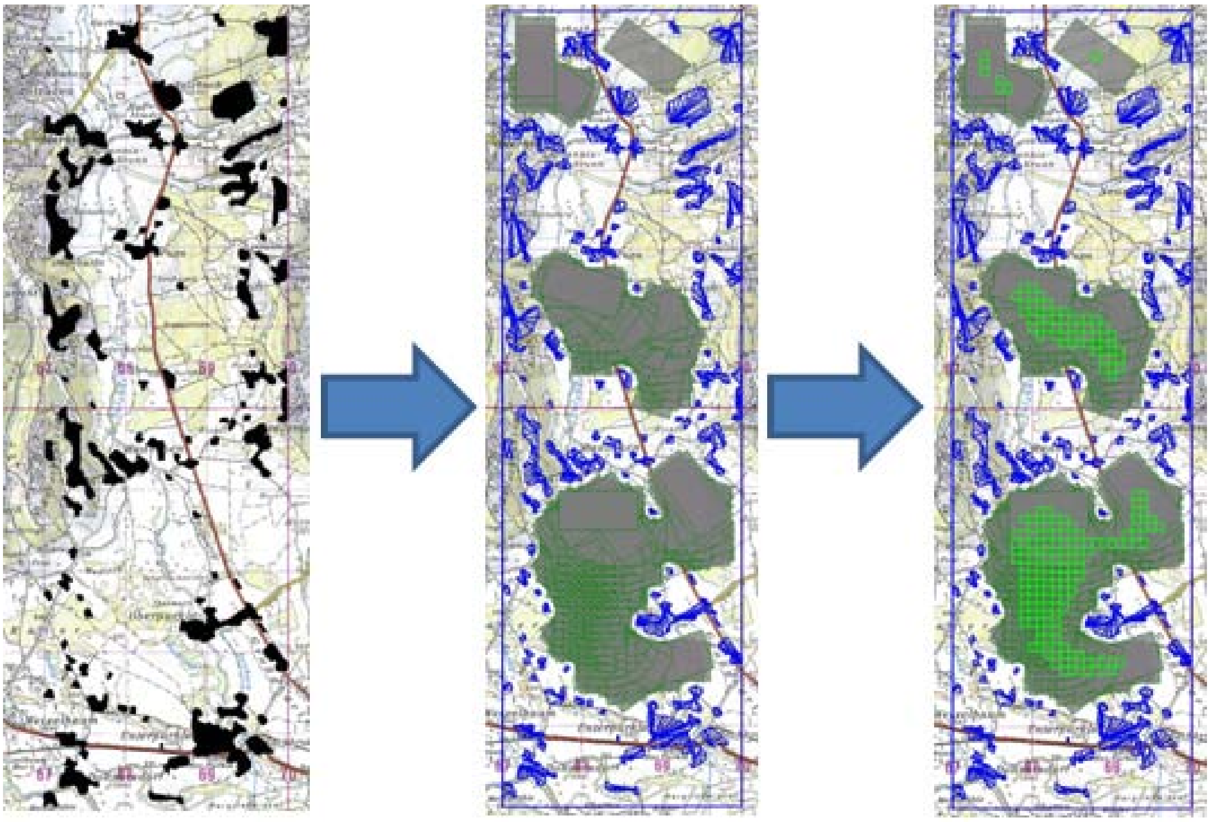

Figure 8: Determination of favorable battle positions: identified dividing areas (left), resulting battle position areas (middle) and center cells of these areas (right).

The intelligent and interesting calculation step is the second one. In the C2DSAS toolkit the enlarging is done by the calculation of the Minkowski sum [Ewald 1996]. Formally, the Minkowski sum of two sets *S* and *T* in the Euclidean space is defined as the resulting set of all sums of elements of *S* and *T*, i.e.

$$S +_M T = \{s + t \mid s \in S, t \in T\}$$

Calculating the Minkowski sum in R^2 can be thought of sliding one geometric shape along the borders of another. In the C2DSAS toolkit every dividing area can be seen as a geometric shape in R^2. The second shape which “slides” along the border of the dividing area corresponds to the spatial troop extend, of which the centre is in the origin of R^2. Figure 9 shows the principle of the Minkowski sum adapted for calculating enlarged dividing areas. By sliding a geometric shape corresponding to the troop size along the border line of a shape corresponding to an identified dividing area the dividing area is blown up. After this has been done for all dividing areas of interest, any cell not corresponding to an enlarged dividing area constitutes a potential centre of a battle position.

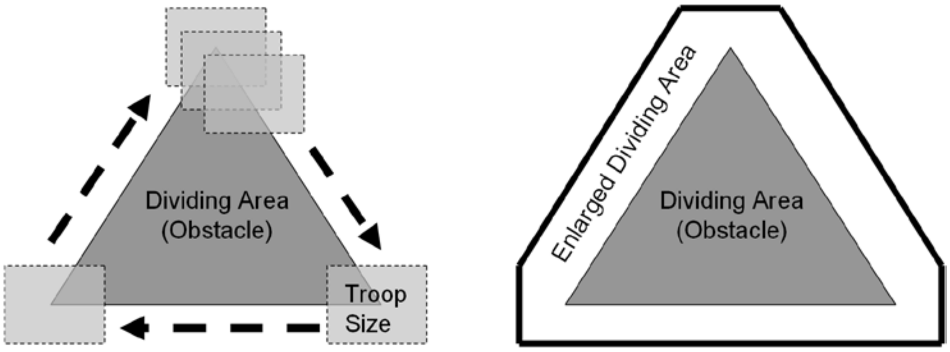

Figure 9: Principle of the Minkowski sum algorithm in the two dimensional case. The Minkowski sum in the 2D case can be thought of like sliding one geometric shape over the edges of another.

Figure 10 shows an example Minkowski calculation done with the C2DSAS toolkit, whereby the dividing areas are marked blue and the calculated enlarged areas are indicated by red cells. In order to consider the different angles the military unit can be aligned, the battle position calculations have to be done more than once, depending on how many different angles are to be considered. In the C2DSAS toolkit there have been considered angle differences of 10° which makes up 18 different directions a unit can be oriented to.

Once possible battle positions have been identified they have to be evaluated with respect to certain criteria. These criteria may include the approaches already presented in this paper like distance to tactically favorable points or reachable areas. Further very important criteria in this context are zones of fire (depending on weapon type) or the possibilities to observe the environment (LOS observation). Figure 11 shows example visibility- and fire zone calculations of the C2DSAS toolkit, whereby the calculations are based on an arbitrary battle position. The assumption made in the example is that the maximum visibility distance is twice the maximum fire range.

In the C2DSAS toolkit ranges can be calculated either in a two dimensional or a three dimensional way depending on whether elevation data is available or not. When calculating two dimensional visibility ranges, only dividing areas like a forest are taken into account. In principle the characteristics of any type of sensor or weapon system could be taken into account to evaluate battle positions. The C2DSAS framework can easily be extended e.g., by non-linear ballistic functions or RADAR coverage models.

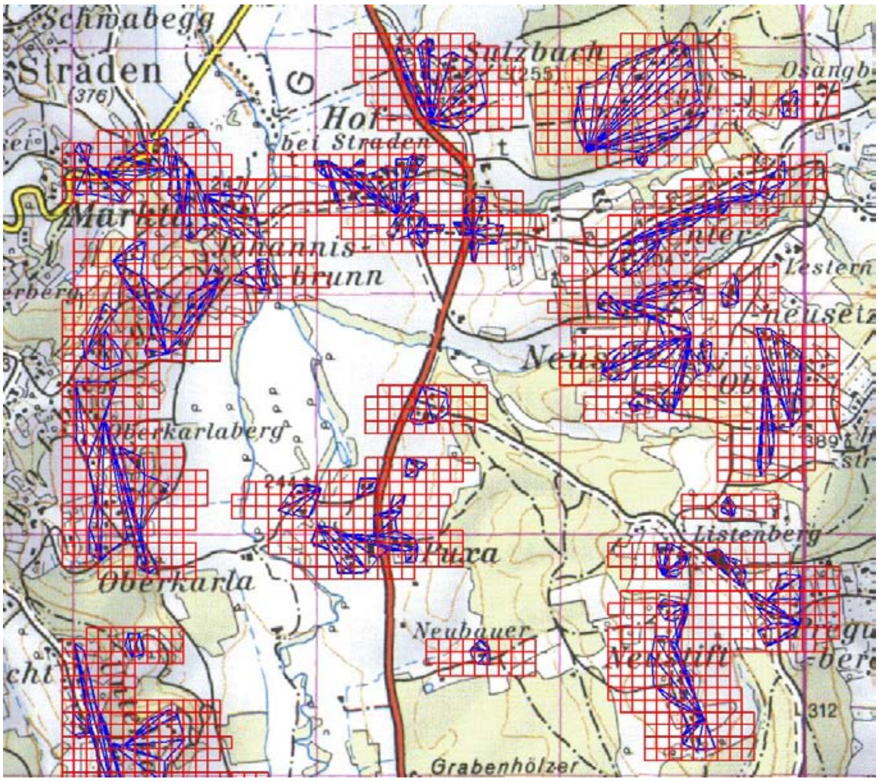

Figure 10: Minkowski calculations done by the C2DSAS toolkit. The dividing areas (blue) are enlarged by means of the Minkowski sum and some predefined spatial requirements of a given unit size.

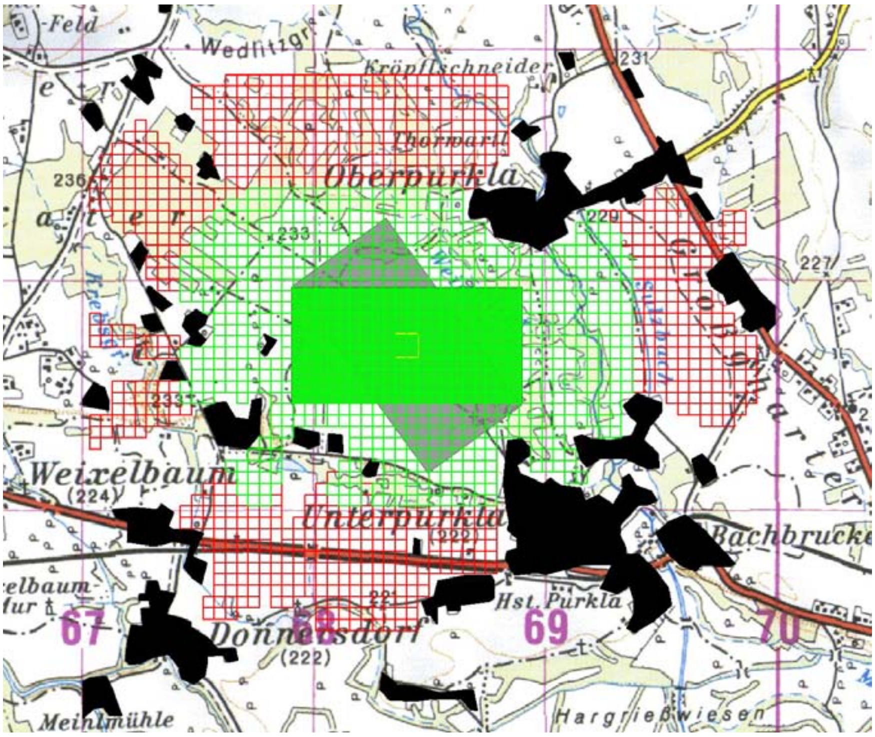

Figure 11: Determination of visibility zones and fire zones based on a given position area. Green cells indicate visible areas which can also be reached by direct fire (i.e. with the given type of weapon system). Red cells indicate areas which are still visible but cannot be reached by fire. Given the center of the position area (green rectangle) other alignments (grey rectangle) are possible. The consideration of different possible alignments may extend the calculated zones.

Another function provided by the C2DSAS toolkit is the determination of "troop formation opportunities" along a given path. Areas where troops are forced to move in a narrow and deep formation are of particular interest. This function can be realized by calculating the distance of the path cells to the dividing areas. This way it is possible to visualize and identify dangerous path areas where it is not possible to regroup troops above certain military formations. Figure 12 shows resulting formation opportunities along a certain path (yellow). The dividing areas are indicated grey. Red areas indicate that there is not enough space even for company formations. Green areas mean that there is enough space for company formations but not for units of bigger size. Unmarked path regions indicate places where it is also possible to organize whole battalions.

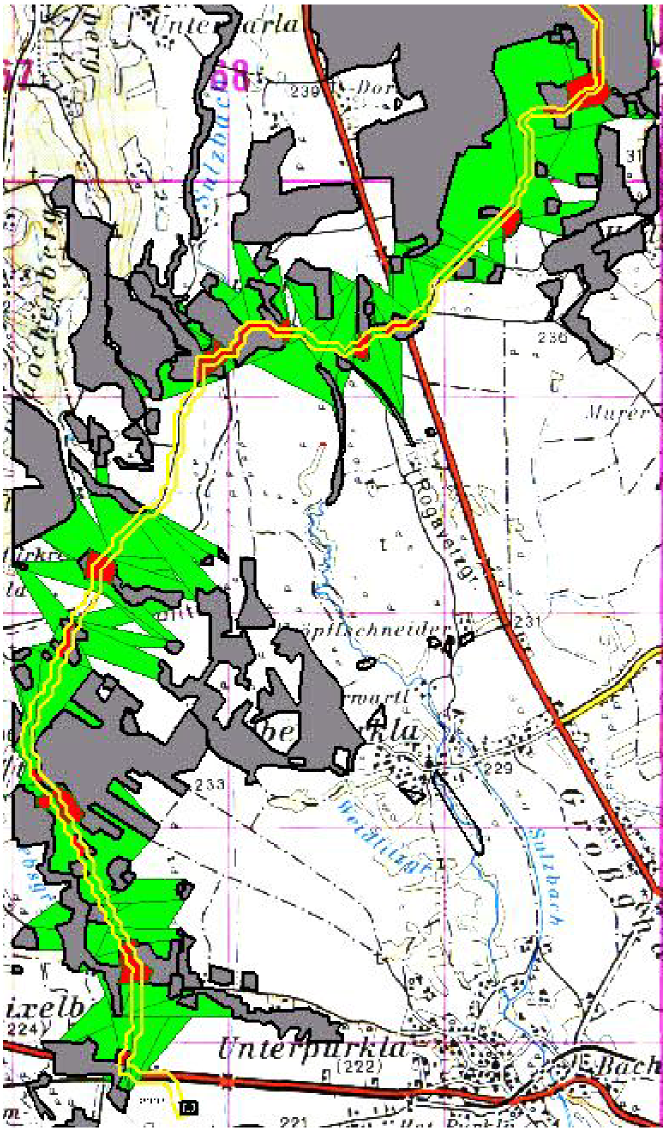

Figure 12: Troop formation opportunities along a given path. Areas of limited formation possibilities are indicated green. Areas with virtually no tactical formation possibilities are indicated red.

5. C2DSAS Prototype

A proof-of-concept prototype has been implemented that is based on the methods and algorithms discussed in the last three sections. The main element of this prototype is the C2DSAS toolkit (see Figure 13).

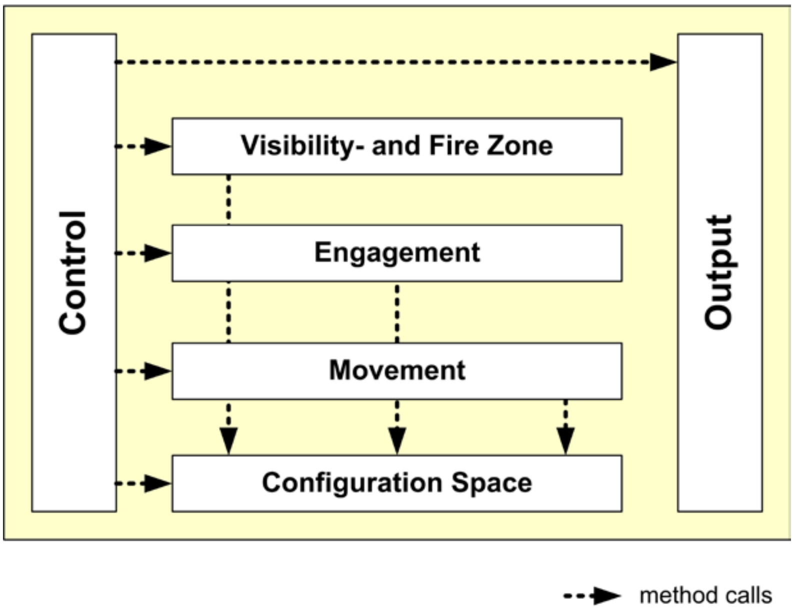

Figure 13: Overall architecture of the C2DSAS toolkit. The arrows indicate component dependencies. For example, the Control component uses functionality of all other components.

Module *Configuration Space* is responsible for building up the internal map representation (i.e. the cell containing quad-tree structures) and the search space (i.e. search nodes containing tree structures), as discussed in Section 2. This component provides the basis for modules *Movement*, *Engagement*, as well as *Visibility- and Fire Zones* which implement the methods and algorithms presented in Section 3 and 4, respectively. The elementary calculations are triggered by method calls from the *Control* module by accepting the input data and coordinating the method calls to the other components. Furthermore, *Control* communicates the input information and the calculated results to module *Output* which provides vector data to be displayed. Figure 14 shows the technical environment and the information flow in the C2DSAS prototype setup.

The user has to provide:

- a vector map
- the “rulebook” (unit parameters, vehicle parameters, tactical rules)
- the operational picture (units and their locations, as well as situational information to be modelled by means of Special Areas)
- a set of requests that determine the expected results e.g., which area can be reached by an armoured infantry platoon within a given time interval, which path should be taken by a support unit to minimize the probability of enemy contact, etc.

The C2DSAS toolkit produces an output file that contains all vector data to be displayed, i.e. all relevant input data as well as the calculated results. The C2DSAS proof-of-concept prototype uses a tool provided by the Austrian Armed Forces to visualize the content of this file.

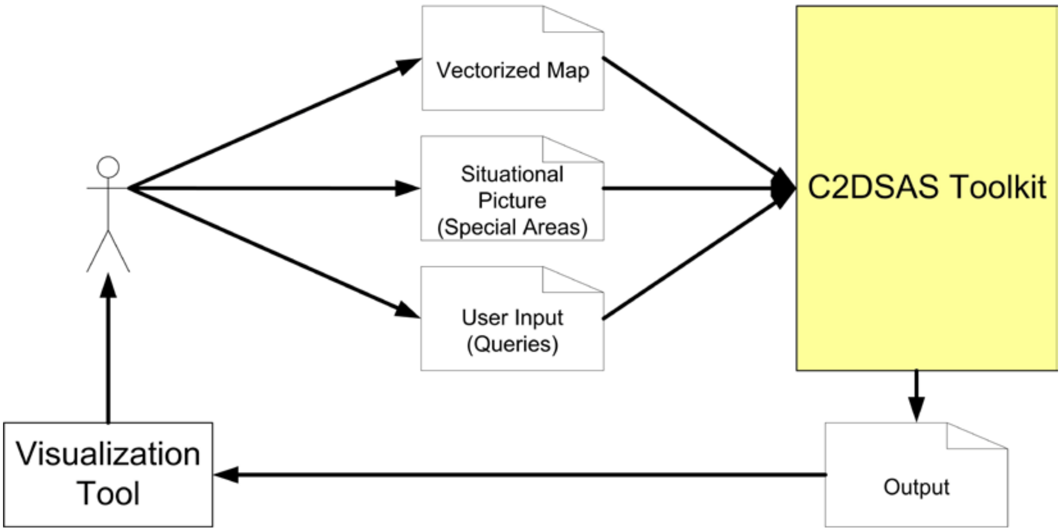

Figure 14: Data and information flow in the C2DSAS prototype setup. Provided different inputs, the C2DSAS toolkit produces an output file which can be displayed by an external visualization tool.

6. Related Work

Whereas a comprehensive and accurate common operational picture can be provided by fielded C2 information systems, advanced tactical C2 planning and decision support is still subject to research and development. Fielded planning support systems for ground forces e.g., the march planning system HEROS-5 of the German Army [Wunder and Grosche, 2009], address logistics rather than tactical aspects.

Military commanders and staff officers have been used to highly elaborate planning techniques based on the experience of decades which are not easily transferable into a computer system. Unlike in other domains where fully autonomous and learning systems already achieve good results [Adams 2001], complex tactical planning tasks still remain subject to human decision making. Moreover, it has been shown that in military command and control, decision making quality is not increased by full automation [Rovira et al. 2007; Burnett et al. 2008].

Although trained commanders and staff personnel may achieve very accurate planning results, time consuming procedures are excluded when quickly changing situations demand immediate re-planning. The research in the fields of artificial intelligence and operations research provide a lot of possibilities in order to provide support for basic planning steps like optimal path determination and thus letting the commanders concentrate on tactical issues rather than planning handcrafts [Bratko 1990; Russel and Norvig 2009]. What is important for the realization of an effective planning support is the fact that the tactical knowledge and experience of the commanders still constitutes the main planning intelligence and therefore should not be given completely into the hand of an AI tool. It is crucial that decision support systems for military planning activities should rather strengthen and augment the problem-solving capabilities of commanders than producing tool dependency [Scales 1998].

Following this idea, the C2DSAS project primarily aimed at the development of a toolkit which empowers commanders and staff officers through the provision of geospatial knowledge products while no limitation is imposed on the tactical planning process itself. In other words, the well established planning process in military staffs is not changed but accelerated and improved while always providing full planning authority to the commander.

Geospatial decision support and its integration into C2 decision making has been investigated both conceptually [Snell and Simpson, 2003] and experimentally [Powell et al., 2010]. In [Snell and Simpson 2003] five key requirements have been identified that are critical to the performance of geospatial planning systems:

1. Appropriate spatial data representation
2. Support for temporal multi-path planning
3. Incorporation of flexible decision making processes
4. Analytical models to tackle well-defined C2 planning problems
5. Consideration of expert knowledge

The C2DSAS toolkit fulfils all of these requirements. Based on vector data as input, raster data as internal map representation, a digital elevation model, and specific analytical functions (currently LOS and direct fire, with extension points for others, such as radar coverage) it provides a set of geospatial decision support products. In that way the C2DSAS toolkit is comparable to other experimental software like the US Army BTRA-BC (Battlespace Terrain and Reasoning Awareness – Battle Command) decision tools [Powell et al., 2010].

7. Conclusions and Future Work

The C2DSAS toolkit constitutes a valuable collection of AI software methods which focus on the tactical planning for ground force operations. The toolkit does not provide methods which facilitate automatic decision making but effectively supports basic planning while keeping the man in the loop. The C2DSAS toolkit provides geospatial knowledge products for (near) optimal path calculations, troop movement projection, determination of visibility zones and zones of fire, as well as methods for the identification of assembly areas and favorable battle positions with very good run-time performance.

The principle which was followed during the development was to transfer the planning process from the still widely used transparent film overlays to the computer screen and moreover provide calculation support for basic planning steps. In this way well-established military planning processes can be kept while significantly speed them up.

The C2DSAS toolkit was designed to allow for generic integration in a broad variety of command and control information systems. However, C2 information systems based on the standardized data model JC3IEDM (NATO STANAG 5525) are able to keep all relevant geospatial, operational, and situational data, as well as the applicable business rules in a single data store and allow for interoperable dissemination of planning results.

Future work will focus on raising the technology readiness level by integrating the current C2DSAS proof of concept prototype into an operationally relevant system environment, preferably a JC3IEDM-based C2 information system available in the Austrian Armed Forces. This task involves

- the development of an integrated tactical planning component based on the C2DSAS toolkit
- the development of a comprehensive, operationally relevant business rule data base
- exploration of novel approaches for visualization of modelling results and planning options in a tactical environment

In particular an advanced user interface which allows for comfortably using the C2DSAS toolkit is to be developed. It should facilitate the communication with the C2DSAS toolkit, as well as provide support to transform a grid map (or maybe even a satellite image) into vector data. Particularly, intelligent approaches should be developed for

- (semi-) automatic element identification in grid maps
- drag and drop update of the situational picture, i.e. an easy way of indicating the position of forces and defining Special Areas
- query formulation by direct graphical interaction, e.g., start and end points for path calculation
- personalized visualization options

Once the C2DSAS toolkit will have been integrated into an operational C2 information system environment, systematic empirical investigations on planning efficiency comparable to the ones reported in [Powell et al. 2009 and 2010] will be conducted.

Acknowledgement

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