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Automatic path planning for improved combat simulation

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Summary

This report summarizes the results of a cooperation regarding terrain analysis between FOI and FFI (Norway) during 2014–2018. The work was done within the collaborative project Terrain Analysis and Synthetic Agents (TASA), under the technical agreement no. 4 FFI-FOI.

The report describes a jointly developed method for path planning for fighting vehicles, including details regarding implementation, terrain models and integration of the developed functions in a simulation-based environment for military staff training and exercise.

Moreover, the report summarizes the experience and recommendations from three demonstrations and workshops with military subject matter experts and researchers within modeling and simulation.

The main results from the collaboration are a peer-reviewed IEEE Computational Intelligence for Security and Defense Applications (CISDA) conference paper and a C++ code base, successfully integrated in different simulation-based applications.

Sammendrag

Denne rapporten oppsummerer resultatet av et samarbeid innenfor terrenganalyse mellom FOI og FFI, i årene 2014–2018. Arbeidet ble gjennomført under samarbeidsprosjektet Terrain Analysis and Synthetic Agents (TASA), som en del av TECHNICAL ARRANGEMENT No 4 FFI-FOI.

Rapporten beskriver en felles utviklet metode for ruteplanlegging for stridskjøretøy, samt detaljer om implementasjon, terrengmodeller og integrering av disse modellene i et simuleringsbasert miljø for trening og øving av militære staber.

I rapporten beskrives også erfaringer og anbefalinger fra tre felles demonstrasjoner, som ble avholdt som seminarer med militære eksperter og forskere innen simuleringsfagfeltet.

Hovedresultatene fra samarbeidet er et konferansebidrag til den fagfellevurderte konferansen 2017 IEEE Symposium on Computational Intelligence for Security and Defence Applications (CISDA), i tillegg til et kodebibliotek i C++.

Contents

1 Introduction

Simulation is a well-established component in military training and education. Using simulations is a key ingredient in efficient staff training and makes it possible to expose trainees to a wide range of situations that are expensive, hazardous or impossible to achieve in the field. Although current simulation tools are powerful and often visually appealing, they have significant shortcomings that limit their usability and flexibility in practice.

One noticeable limitation concerns the behaviour of simulated entities in the terrain. In simulations of military operations entities need to handle different situations and carry out given tasks in a realistic manner. Many tasks involve movement from one position to another and the choice of route that the entity should follow depends on several factors, e.g. factors related to terrain properties, enemy forces and their positions, or strategy and tactics.

The overall scope of our work is to enhance battalion staff training by improving the terrain reasoning abilities of the simulated entities. By enhancing the path planning functionality of simulated fighting vehicles they will be able to move more realistically and in a more adaptable way than is currently the case in most simulation frameworks used for military training. The goal is to develop a path planning functionality realistic enough to ensure that what is played out in the simulation correlates with the expectations and intent of the training staff.

1.1 Joint efforts on terrain analysis

The need for improved behaviour of simulated entities was the starting point for joint work on automated terrain analysis carried out by FOI (Sweden) and FFI (Norway) during 2014–2018, within the collaboration project TASA[1].

The joint terrain analysis work had the following goals:

i) Develop a new path planning method.

ii) Implement it in a computationally efficient, platform independent software library.

iii) Integrate it in a framework for simulation-based staff training.

[1] Terrain Analysis and Synthetic Agents, TECHNICAL ARRANGEMENT No 4 FFI-FOI.

2 Path planning for fighting vehicles

Our aim was to develop a situation-dependent path planning method that can take several heterogeneous aspects into account simultaneously and easily switch between path planning for different types of situations. Here we briefly summarize the concept, which is further elaborated in [1] and [2], along with details and examples of how to formulate measures for different aspects.

2.1 Rationale

At the core of the approach lies the combination of three conceptually different types of factors:

- Static terrain properties (accessibility and maximum speed in different types of terrain, visibility in different directions, etc.)
- Dynamic factors (threat level, line of sight to nearby targets, etc.)
- Tactics (move fast, stay hidden, etc.)

Other factors such as the influence of weather, seasonal variations and lightning conditions have not been explicitly taken into account. The reasons are that from a conceptual point of view, their effects can be addressed to a large extent by adjusting accessibility and visibility parameters accordingly, plus that establishing a mapping between weather effects and behaviour in the terrain was deemed beyond the scope of the work.

The main novelty of this approach is the inclusion of the tactics dimension. It gives the user (or the host simulation program) explicit control over how a task should be carried out, so that the computed path is not necessarily the shortest or fastest one, but the one corresponding to the best trade-off between sometimes conflicting aspects.

2.2 Cost function

Moving from one place i to another j is associated with a cost described by the following cost function:

$$C(i,j) = \frac{\sum_{k=1}^{N} 2^{p_k} w_k(i,j) d(i,j)}{\sum_{k=1}^{N} 2^{p_k}} \tag{2.1}$$

where N is the number of categories, $w_k(i,j) > 0$ is the cost according to category k for moving from i to j, $d(i,j)$ is the Euclidian distance between i and j, and $(0 < p_k < 10)$ is the priority of category k.

The choice of a weighted mean cost measure that separates prioritizations and category costs was a consequence of previous work aiming at suggesting cost functions with desired mathematical properties.

2.3 Categories

A central part of the work on path planning has focused on formulating and testing quantitative measures representing various aspects on path planning, and – most of all – tuning parameters to achieve good performance. Here follows a brief overview of the categories. More discussions and implementation details are given in [2].

- **Cover**: The category cover reflects the degree to which a vehicle at a particular position is physically protected if fired upon from enemy positions.

- **Visual concealment**: The idea behind visual concealment is to reflect how difficult it is to spot a vehicle by enemy forces with electro-optical sensors in the given terrain. We seek a measure that is not based on precise knowledge or assumptions of the whereabouts of enemy units. In many cases, especially in reconnaissance scenarios, the exact position of the enemy units cannot be assumed known. Here, we loosen that condition and assume only that the direction towards the enemy forces is known. Based on that assumption, we seek a measure favouring movement that minimizes exposure in that direction. We do this by defining a set of sectors in a number of directions (here: 8) and computing a visual concealment measure for each direction (Figure 2.1).

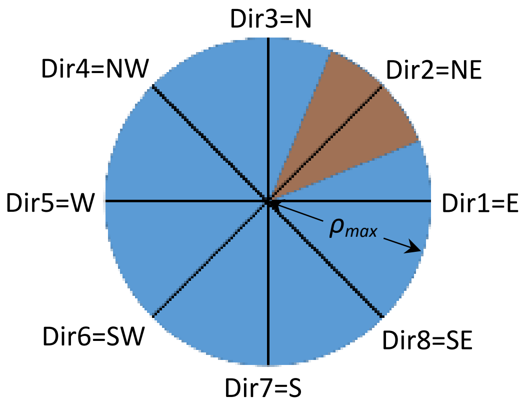

Figure 2.1 Computations are made in cones for a number of directions.

We formulate a heuristic-based visual concealment weight at position x_0 for direction D as:

$$W_{V,D}(x_0) = \frac{1}{|D|} \sum_{x \in D} \frac{\sin(f_z(x))\rho(d(x, x_0)) + 1}{2} \tag{2.2}$$

where $|D|$ is the number of pixels in the sector corresponding to D, $d(x,x_0)$is the 2D distance between x and x_0, $\rho(x)$ is a thresholded linear function such that $\rho(0)=1$ and $\rho(d \geq d_{max})=0$ where d_{max} is a chosen max search distance, and

$$f_z(x) = \frac{Z_{DSM}(x_0) - Z_{DTM}(x)}{d(x, x_0)} \tag{2.3}$$

where h is the height of the observer above the ground, Z_{DTM} is the elevation of the Digital Terrain Model (DTM) (bare earth), and Z_{DSM} is the elevation of the Digital Surface Model (DSM) (terrain with vegetation). The purpose of the function ρ is to reduce the influence of elevation differences farther away from the vehicle.

- **Threat:** The threat category comes in play when the positions of enemy units are known or assumed. Via the threat weight entities are encouraged to stay out of the weapon or sensor range of known enemy entities.

- **Accessibility:** The accessibility category represents how preferable a terrain type is, e.g. with respect to the chance of damaging the vehicle or getting stuck.

- **Time:** The amount of time needed to move to a location depends on the distance and the terrain types along the path. Each terrain type is assigned a speed value that is considered a mean value for movement in that type of terrain.

- **Acoustic concealment:** This was done by specifying a typical sound source and estimating the acoustic detection range in a particular direction, using ISO and MIL standards for sound attenuation and detection limits.

2.4 Path profiles

Finding suitable weights and priority values for each of the categories requires thorough testing and detailed knowledge of the underlying nature of the parameters. To facilitate usage of the proposed algorithm a number of higher-level behaviours are proposed, each corresponding to a set of parameters. In this way the host simulation or user can request a certain type of path rather than supplying a particular set of parameter values. This abstraction also increases the flexibility and facilitates code maintenance and development, as low-level modifications can be made without affecting the application interface. Some examples are shown in Figure 2.2.

- **Move:** Standard movement in areas where no enemy forces are expected. Accessibility and speed are prioritized, while concealment and cover are less important.

- **Move cautiously:** Accessibility and speed are prioritized less, while avoiding threats and staying in cover become more important.

- **Reconnoitre:** Typical stealth mission behaviour. Cover, concealment and staying away from threats are important, while moving quickly is even less important than in the Move Cautiously behaviour. The result is typically circumventing and longer paths.

- **Attack:** Trying to stay hidden while moving in to attack enemy forces. Cover is more important than accessibility and speed.

- **Hasty attack:** Staying hidden is low priority. This profile emphasizes speed compared to the Attack profile. Intended for situations where a vehicle is ambushed or the task is to support own forces already in combat.

Figure 2.2 Examples of path profiles drawn with blue lines. Left: "Move" ignores the presence of a threat along the path and prefers movement on road. Middle: "Move cautiously" stays away from the threat while still preferring easily accessible terrain. Right: "Reconnoiter" stays away from roads and prefers terrain that provides cover and low visibility.

3 System design recommendations

During the first phase of the TASA project, an important task was to break down the overall needs into recommendations concerning the actual implementation of the terrain analysis software components. These design recommendations were collected in [3]. Below is a summary of system design recommendations that have guided the implementation throughout the project and make a good starting point for future development of similar tools.

3.1 Terrain models

- The terrain model must be compatible with both the terrain analysis tools and host applications. This is needed to ensure correlation between the terrain analysis results and the simulation as a whole.

- The geographical extent should be scenario-dependent. The system should be able to adapt to the size of the geographical area used in a specific scenario. In practice, for a ground battalion level scenario, this could correspond to distances of about 10–20 km.

- The resolution of the terrain model should be between 1–10 m (for ground vehicle simulation). This is a suitable compromise between simulation fidelity, system performance and the availability of geographical source data.

- Access to source data should be ensured. Having access not only to an already processed 3D model, but also to the underlying source data used for creating the model, provides the possibility to perform terrain queries, make different thematic visualizations and to use it for debugging purposes.

3.2 Architecture

- Functionality should be divided into core library, pre-processing applications and demonstrators. This is important to avoid duplication of functionality and to maximize code reusability.

- Application-specific and immature code in the core library should be avoided. Only general functionality and robust code goes in the core library.

- Configuration should be simple. This is important to allow for quick setup of development environments, testing and to easily create applications.

- The design should be plug-in based. A plug-in based approach facilitates replacement or addition of functionality.

3.3 Compatibility

In order to streamline the integration of the functions with different applications, the system should:

- Support common terrain data formats, such as GeoTIFF, OpenFlight, and Shapefiles.

- Be platform independent (code and build environment).

- Support several programming languages. The code is written in C++, but modules for use with other languages can be built using SWIG[2].

3.4 General

- Avoid dependencies with strict licenses.
- Use existing software components when possible. Focus development on integration and creating novel functionality, rather than redeveloping basic functionality.
- Develop debugging tools. As development progresses, such tools will prove invaluable for testing and evaluating purposes.
- Unit tests. Test software in its entirety to ensure proper functionality in the case of third party library upgrades, hardware changes or operating system updates.

4 Implementation

The algorithms developed during the TASA collaboration project were implemented in the following ways.

4.1 Geo Analyst Library

The Geo Analyst Library (GAL), is a C++ software library developed by FOI for computationally efficient terrain analysis and integration with a range of host applications. GAL is designed around a flexible plug-in architecture where the user can easily extend or replace different modules. An example that utilizes the plug-in architecture is the navigation mesh implementation. The default implementation uses the Recast open source library[3] but we foresee that some users may want to swap to a proprietary library or experiment with other search algorithms. Another example is the terrain interface used by the path planner for terrain queries. However, the actual terrain implementation will vary depending on the target simulation system. By utilizing the plug-in architecture the user can select a terrain system implementation that piggybacks on terrain query functionality found in the target simulation system.

[2] Simplified Wrapper and Interface Generator, accessible at http://www.swig.org.
[3] Recast navigation library available at https://github.com/recastnavigation, accessed on 28th February 2019.

4.2 Terrain pre-processing tools

To support path planning, a navigation mesh first has to be built from input geometry/3D models and user defined parameters. A command line conversion tool for generating geometry is provided in GAL, called GALConv. GALConv uses the OpenSceneGraph (OSG)[4] library for reading common terrain database formats like OpenFlight. GALConv can also read Shapefiles holding triangulated irregular network (TIN) data, generated with geographic information system (GIS) software like ArcGIS or GlobalMapper. When the input geometry is generated the command line tool GALNavMesh generates the actual navigation mesh from the input geometry. When using this tool you specify input parameters like entity radius (the radius of the entity using the navigation mesh, such as vehicles or dismounted soldiers), entity height, entity max terrain slope, max climb height of entity, etc. This implies that you should generate specific navigation meshes for each entity class. In this project, we focus on armored vehicles and hence generating only one mesh sufficed. Terrain movement differences between track and wheel vehicles are taken into account through different parameters of accessibility and speed on different materials.

4.3 Terrain Analysis library

The Terrain Analysis library (TALib) is a library jointly developed by FOI and FFI on top of GAL. TAlib implements the path planning approach described in section 2. TALib utilizes the navigation mesh functionality in GAL but injects its own cost functions (as described in section 2.2). It also provides a simple entity model that is used by the path planner to take platform type and properties into account. For instance, accessibility weights for a main battle tank might be very different from accessibility weights for a car. Therefore, TALib requires not just the target position for path planning, but also the entity type.

TALib also includes a test application that can be used to evaluate weights for the categories described in Section 2.3. The weights can then later be used to create path profiles described in section 2.4.

Figure 4.1 shows a screenshot of the test application developed for test and evaluation of the functions in TALib. Sliders and check boxes provide the means to control category weights and other important parameters.

[4] Open source 3D graphics toolkit, available at http://www.openscenegraph.org.

Figure 4.1 *Test application for TALib. By adjusting the sliders in the search settings dialog, the category weights can be controlled. The categories are threat, time, accessibility, concealment, and cover. In the profiles dialog, the preconfigured search profiles can be activated. When a profile is selected, its weights are reflected in the search settings sliders.*

4.4 Integration with simulation framework

The code libraries were integrated with the following simulation frameworks.

4.4.1 SWAP

In order to test the path planning algorithms, we integrated GAL with the Simulation-Supported Wargaming for Analysis of Plans (SWAP) system. The SWAP system attempts to simplify the simulation of large, manoeuvre-based operations by taking orders at a high level and breaking them into smaller tasks that can be executed by a computer generated forces (CGF) system.

SWAP accomplishes this by representing each unit in the order of battle as an agent in a hierarchical multi-agent system. When an order is given to an agent, the order is broken down into simpler tasks for its subordinate agents. The subordinate agents break the order down further, until it reaches the lowest agents in the hierarchy, which usually are in direct control of simulated units in the CGF. The artificial intelligence of these agents is based on the context-based reasoning paradigm. Both SWAP and context-based reasoning are described further in [4].

In order to make the path planning algorithms available to SWAP, we created an interface that implemented the Web Processing Service (WPS) standard, as defined by the Open Geospatial Consortium (OGC). When calling the service, a user must supply the start and end points of the route, and may optionally supply other parameters, such as entity data, positions of enemies, or priority weights for the different aspects of path planning. The service returns a route as a LineString in the GeoJSON format. More details about this service, as well as a description of the WPS standard itself, can be found in [5].

4.4.2 Demo application

Our main demo application involved running a scenario within the SWAP system. The multi-agent system had several sets of priority weights stored as path planning profiles, and decided which profile to use on the basis of the context the agent was currently in. For instance, an agent performing an administrative movement would choose the “move” path profile, while an agent tasked with scouting for enemies would choose the “reconnoitre” path profile.

In order to showcase the dynamic nature in which the route planning service could be used, the multi-agent system was programmed to re-plan an agent’s route whenever a new enemy was discovered. Since the positions of enemies were sent to the route planner as part of the input parameters, the new route could differ drastically from the old one, depending on how much importance the path profile placed on avoiding enemies.

5 Scenario

For development, test and demonstration, an already existing scenario was chosen that depicts a fictive military operation mainly involving tanks and fighting vehicles in a 20x20 km^2 area around Larvik, Norway (Figure 5.1). The scenario is described in detail in [6]. The scenario was deemed especially suitable for the terrain analysis work as it spans different kind of terrain, including mountainous forest areas, movement-restricting features (e.g. water), and open, flat terrain.

5.1 Vignettes

In order to study certain situations in more detail, the scenario was further subdivided into three vignettes. Each vignette describes events occurring within a short time window, and includes the initial starting position of all vehicles, as well as the missions to be carried out by the blue and red forces, respectively (Figure 5.2 and Figure 5.3).

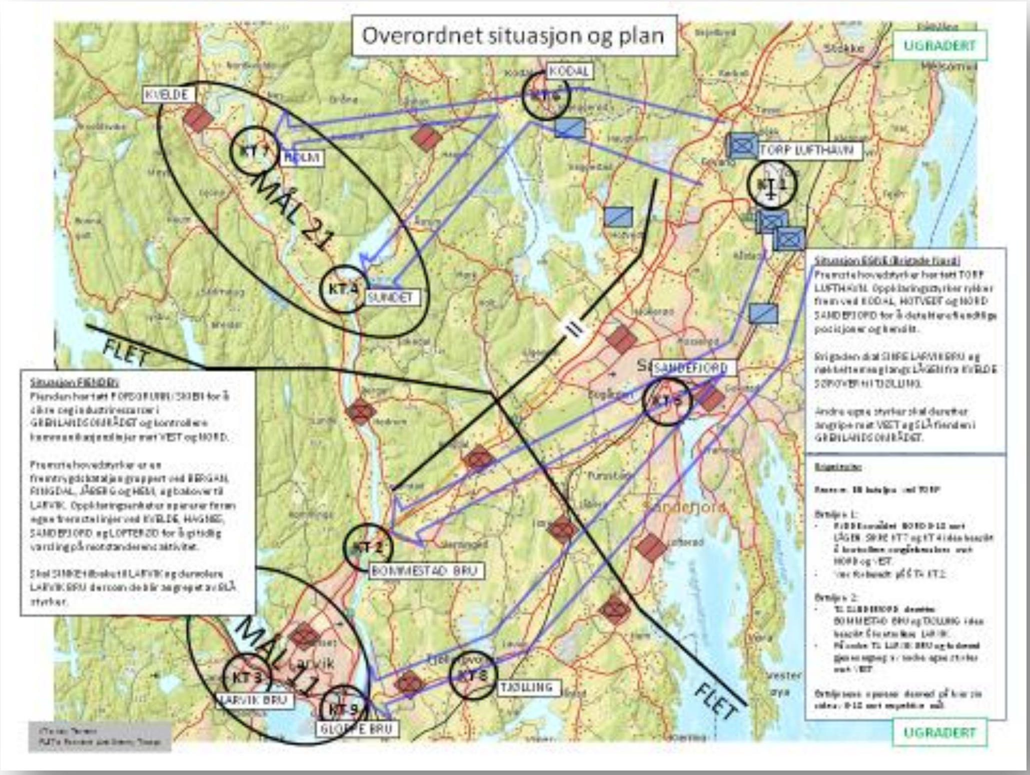

Figure 5.1 An overview of the Larvik scenario, which the demonstration and subsequent end user feedback was based on.

5.2 Terrain

In the scenario we used an existing terrain model generated by FFI. The model was generated for VR-Forces and was based on 10 m elevation data and ground material classifications. A strong reason to base the navigation mesh on this terrain was to be able to demonstrate the new path planner in VR-Forces. The terrain model is illustrated in Figure 5.4.

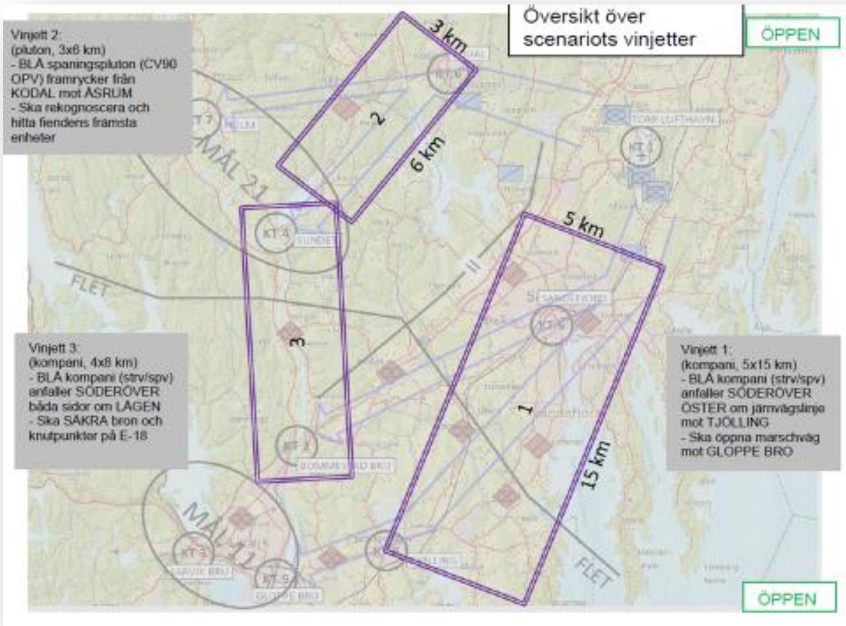

Figure 5.2 The scenario contained three vignettes. Each of these described a set of events that occurred within a short time window.

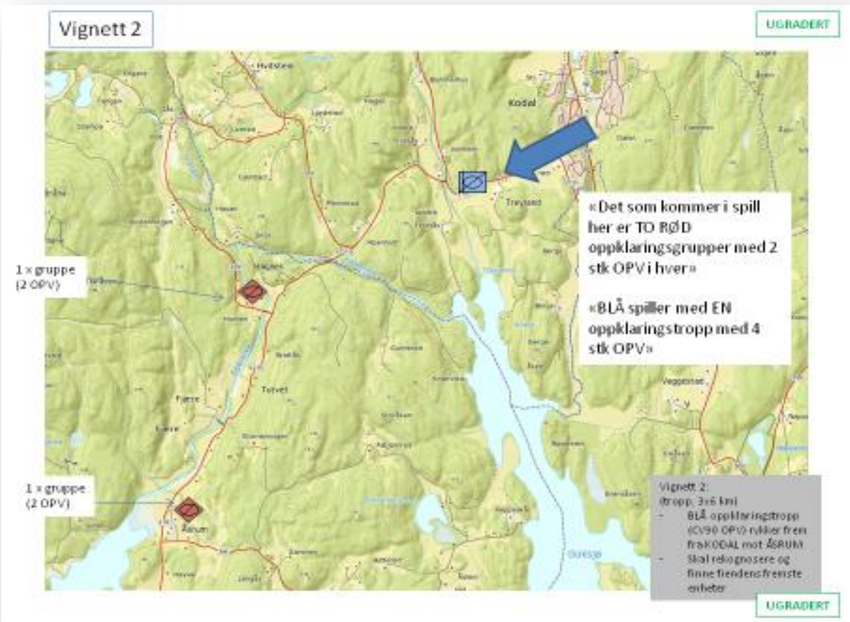

Figure 5.3 Example of a vignette in the scenario.

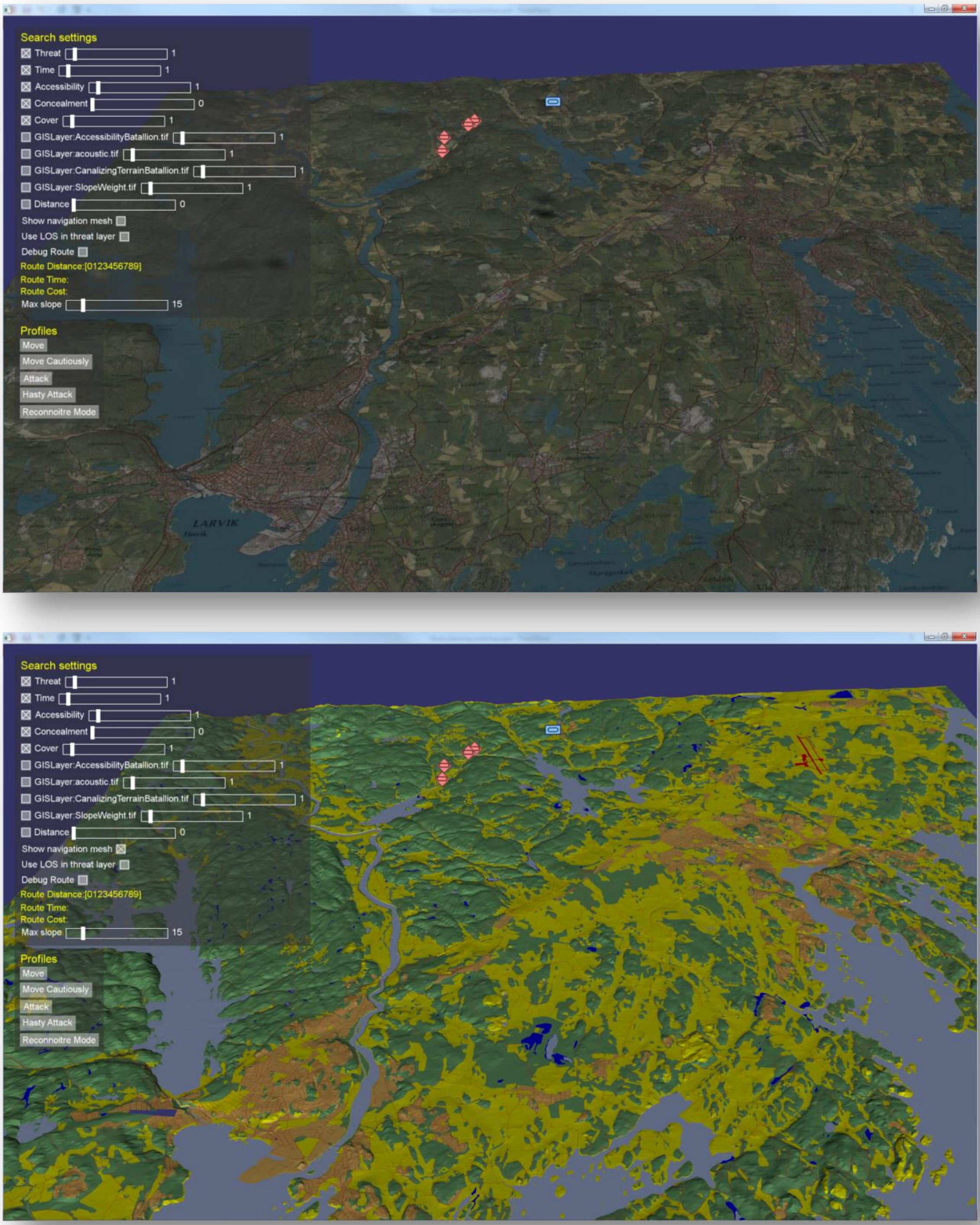

Figure 5.4 The 3D terrain model used in the path planning work. Top: Textured with satellite photo. Bottom: Textured with material classes (green: forest, yellow: open terrain, orange: built-up areas, light blue: water, dark blue: undefined, red: specific objects e.g. airport).

6 Workshops with subject matter experts

To get feedback from Subject Matter Experts (SMEs) on the tools and methods developed, two mid-term workshops were arranged: March 31, 2016 at FFI, Kjeller, Norway and April 8 2016 at Ledningsträningsanläggningen (LTA), Skövde, Sweden. The focus was on path planning.

We used the vignettes from the Larvik scenario for discussions with and among the workshop participants on how they would solve the respective tasks, e.g. choose a route for a reconnaissance mission. The participants drew routes/plans by hand on paper maps to visualize their way of thinking in a graphical manner (Figure 6.1). Next, we used our visualization tool (Figure 6.2) to see if we were able to produce similar routes and/or alternative routes. This exercise was well suited to discuss if and how the presented methods could add value compared to existing systems, and what future improvements could be made to further increase their usefulness.

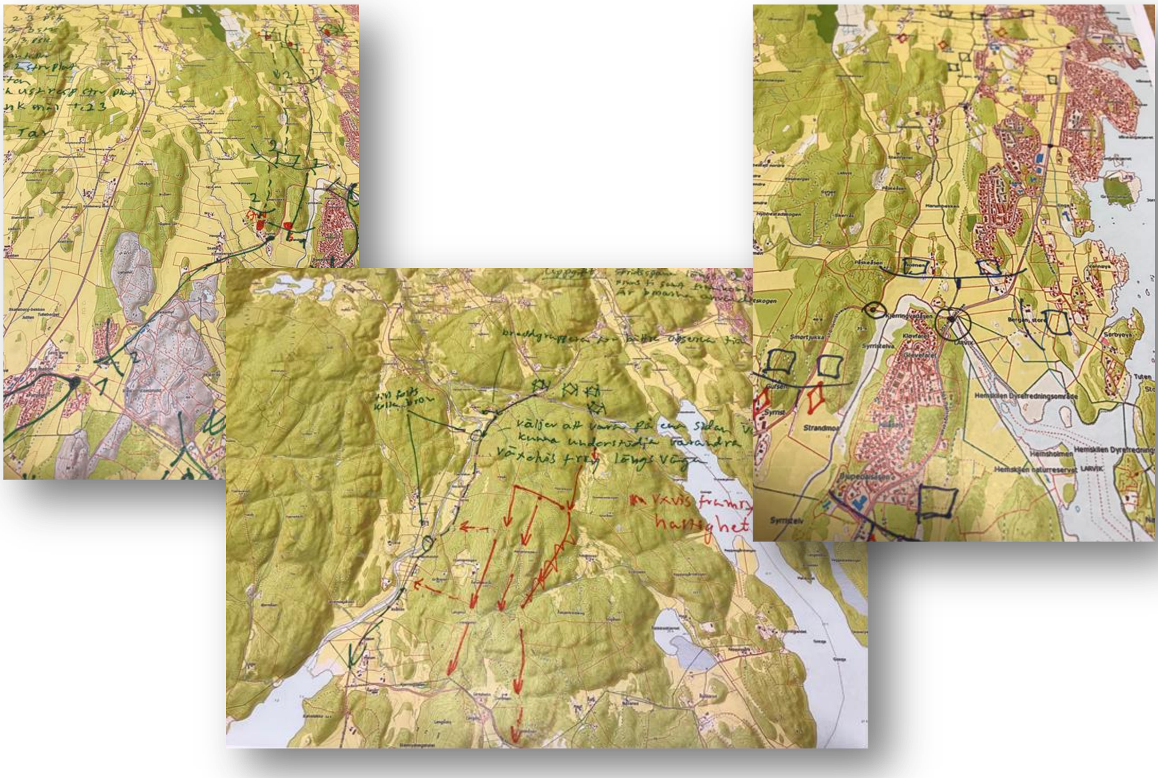

Figure 6.1 Some examples of the feedback given by subject matter experts in the workshops, concerning how they would plan a path in order to carry out the orders given in the vignettes.

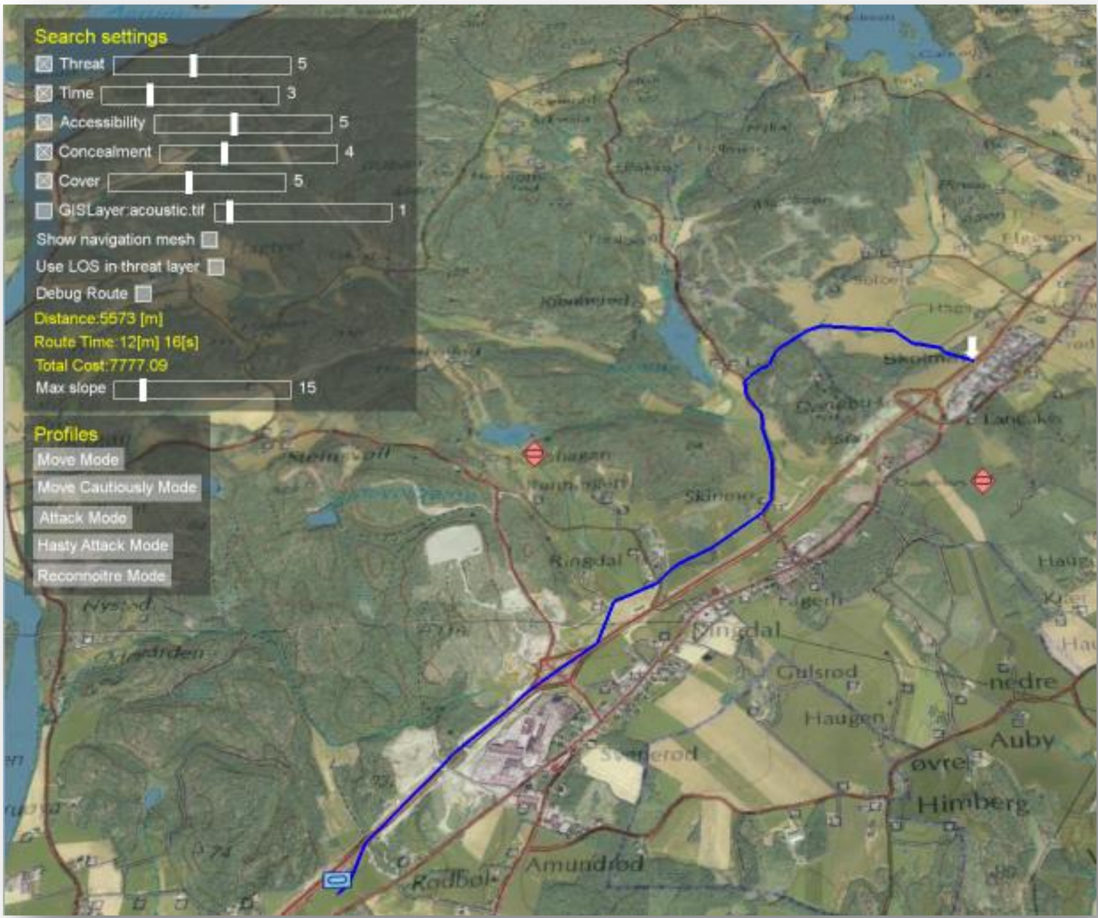

Figure 6.2 The visualization tool used in the workshop to edit path planning parameters and display the result.

6.1 Results

The work and discussions in the workshops gave valuable input to further development of the tools and interesting comments and feedback. Here is a summary of desired additional functionality:

- Support for automatically finding vantage points in the terrain, for observation and attack. Such points are generally characterized by the possibility to move quickly from cover to observation and back. They are not necessarily the highest points in the terrain as those are the most predictable ones.

- Identify canalizing and key terrain automatically, as it influences the choice of waypoints as well as path taken between them.

- A possibility to include acceptable risk level (e.g. low, middle, high) in the planning process.

- Add indirect fire, as it influences the choice of path, e.g. the most obvious avenues of approach should be avoided.

- Take uncertainty into account in the analysis, e.g. model natural variations in vehicle speed and account for uncertainties in threat positions.

6.2 Discussion

Our main conclusions regarding automatic terrain analysis and path planning after these workshops were that:

- Automatic path planning is useful to show options.

- We were headed in the right direction with path planning, and the functionality should be able to enhance simulation capabilities. For instance, by reducing the work load on controllers for opposing forces and at the same time improving CGF behaviour.

- Path planning is also interesting for planning scenarios, for instance by improving the planners' understanding of time and thus potential courses of action. The tool should also be able to evaluate a specific, user-defined route in terms of exposure along route, travel speed, etc.

- For decision support, planning is done more in terms of waypoints. How to move between waypoints is less interesting.

- Some of the path planning factors identified as necessary by the SMEs can be accounted for by altering already existing parameters. For instance by introducing new entity types, altering cover threshold or sensor ranges, generating multiple navigation meshes, etc.

7 Final demonstration

At the end of the project, a final demonstration was given at FFI on March 21, 2018. Here the project demonstrated the path planning tool integrated with SWAP and VR-Forces to show its use in a practical situation. Using the same scenario as in the previous workshops it was shown how simulated forces first chose a quick path in the absence of known enemy forces and then automatically re-planned to a slower but safer route as enemy forces were detected. Figure 7.1 and Figure 7.2 show screenshots from the systems used during the demonstration.

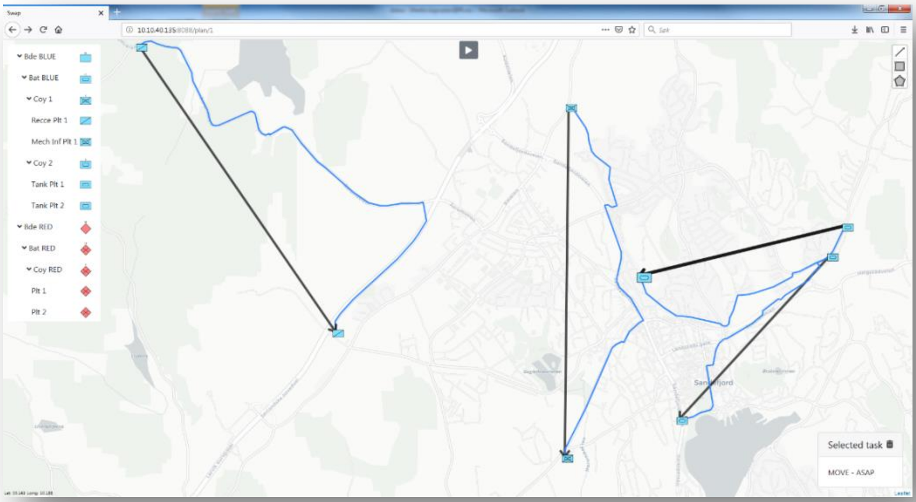

Figure 7.1 The result from the path planning algorithm integrated into the SWAP path planning framework. Given an order and waypoints that need to be passed (if any), SWAP calls the path planner algorithm that returns a path corresponding to the desired profile. In this figure, the Move profile was chosen.

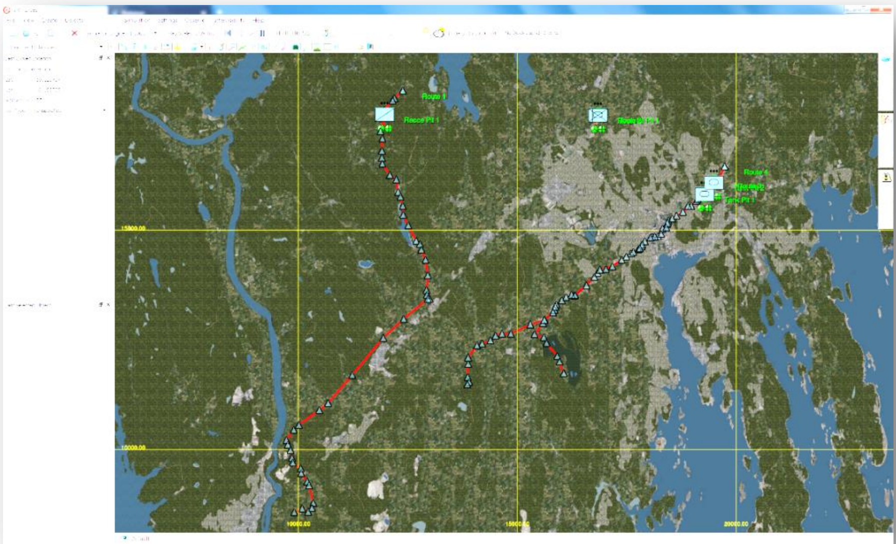

Figure 7.2 The jointly developed path planning method integrated into VR-Forces for more realistic combat simulation.

8 Conclusions and discussions

In this collaborative project we have developed path planning techniques and tools that have found acceptance both among military subject matter experts as well as academia. We have created a solid basis, in terms of both knowledge and computer code, to continue development in various contexts jointly or separately in different national projects.

The achievements have been made possible through a close collaboration between the parties, including sharing and co-development of code and integration efforts. The key has been to strike the right balance between overlapping and complementary competences; a large enough overlap to enable joint development, understanding and evaluation of key components, while complementary enough to create synergic effects, spawning new ideas and learning from each other.

Based on the discussions during the workshops, it is clear that path planning and terrain analysis is also useful for decision support and planning of military operations. However, the fidelity and level of detail of the analysis is limited by the quality of available geographical data. Many of the types of analyses that are of interest will require different and perhaps more detailed terrain data than what was available in this project. We note, however, that a large number of new high-fidelity, high-resolution data are emerging, e.g., 3D terrain models made from aerial photos. This data may be easily incorporated in the proposed analysis framework.

So far, the techniques have only been validated on a conceptual level – not assessed in the field. Although the results look promising, it is too early to say exactly how well a path suggested by the tool corresponds to the preferred path in the actual terrain.

8.1 Future work

As far as future work goes, it is clear that the challenge of automatically detecting suitable end-points of the paths must have a high priority. Often, path planning is done in terms of waypoints rather than continuous trajectories. In fact, how to navigate between waypoints is often less important or even neglected in the planning stage. Future work should therefore look at how to determine good locations for observation/reconnaissance and attack. In addition, using terrain analysis tools for identifying areas where enemy forces may appear due to canalizing terrain effects, hence supporting planning as well as scenario design, is also important.

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About FFI

The Norwegian Defence Research Establishment (FFI) was founded 11th of April 1946. It is organised as an administrative agency subordinate to the Ministry of Defence.

FFI's MISSION

FFI is the prime institution responsible for defence related research in Norway. Its principal mission is to carry out research and development to meet the requirements of the Armed Forces. FFI has the role of chief adviser to the political and military leadership. In particular, the institute shall focus on aspects of the development in science and technology that can influence our security policy or defence planning.

FFI's VISION

FFI turns knowledge and ideas into an efficient defence.

FFI's CHARACTERISTICS

Creative, daring, broad-minded and responsible.

Om FFI

Forsvarets forskningsinstitutt ble etablert 11. april 1946. Instituttet er organisert som et forvaltningsorgan med særskilte fullmakter underlagt Forsvarsdepartementet.

FFIs FORMÅL

Forsvarets forskningsinstitutt er Forsvarets sentrale forskningsinstitusjon og har som formål å drive forskning og utvikling for Forsvarets behov. Videre er FFI rådgiver overfor Forsvarets strategiske ledelse. Spesielt skal instituttet følge opp trekk ved vitenskapelig og militærteknisk utvikling som kan påvirke forutsetningene for sikkerhetspolitikken eller forsvarsplanleggingen.

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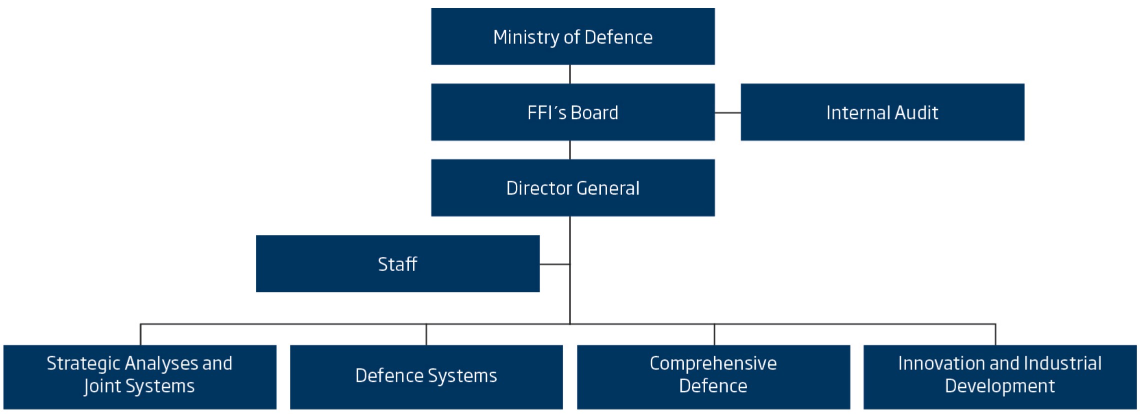

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