Abstract Submission

19th ICCRTS

"C2 Agility: Lessons Learned from Research and Operations"

Title of Paper:

Investigating constraint-based approaches for the development of agile plans

Topic(s):

Topic 1: Concepts, Theory, and Policy

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Investigating constraint-based approaches for the development of agile plans

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1. Abstract

The ability to conduct coordinated interdependent, full spectrum actions by widely dispersed teams throughout the width and depth of the battlespace, ordered and connected within an operation design created to achieve the desired end state is key to the Canadian Army. This concept has been called Adaptive Dispersed Operations (ADO). Defence Research and Development Canada (DRDC) has investigated different concepts to support a battle group commander conducting ADO. A key problem occurring in existing C2 systems is related to the fact that, during the execution of an operation, the details of a plan are most likely subject to change due to a highly dynamic, partially uncertain and complex environment. However, changes without impact on the end state of an operation should not justify continuous time consuming adaptation. Accordingly, due to the high tempo of ADO operations, tactical planners should only adapt plans when required. For monitoring ends, an intelligent notification mechanism becomes key in such a context. For example, one could wonder if a "small" delay of the task schedule is really meaningful to the achievement of the operation and hence requires special attention of the commander. This paper presents a temporal and spatial constraint-based planning approach aiming to support the development of robust plans. Robustness is sought (*i*) to provide more flexibility in the execution of actions and (*ii*) to reduce need for replanning when missions face moderate unexpected disturbing events. The proposed approach is illustrated by implementing a mission plan in the Tactical Planning and Execution Management (TPEM) prototype developed by DRDC.

2. Introduction

Future security environments are envisioned as having considerable uncertainty, rapid change and a high degree of complexity (DLCD, 2009). Evolving into an environment that is not only militarily driven, the Canadian Army will be required to consider the multiple dimensions of the situation, including geopolitical, social (ethnic, religious, ideological), economic, resource, environmental, science and technology, military, and security drivers (CFD, 2010). The coexistence of these different dimensions will have the effect that future conflict zones are not likely to have clear boundaries, making them highly fluid and multidimensional. Distinction between friend and foe or neutral will be a challenge by itself. Affiliations will likely change over short periods of time according to the evolution of a highly dynamic situation. Future foes are expected to adapt themselves to exploit any

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opportunity to become a threat that may cover a multitude of dimensions. Accordingly, enemies can operate while being dispersed over a wide geographical area or not.

To face the challenge of the future, the concept of Adaptive Dispersed Operations (ADO) has been proposed. It is characterized by "the ability to conduct coordinated interdependent, full spectrum actions by widely dispersed teams throughout the width and depth of the battlespace; ordered and connected within an operation design created to achieve the desired end state." In this concept (DLCD, 2007), the Canadian Army envisages employing highly adaptable tactical forces dispersed – in terms of time, space, and purpose – across the entire battle space in order to create and exploit opportunities, increase the tempo of operations, and overwhelm the enemy's understanding of the battle space. The ability to conduct coordinated yet independent, full spectrum actions by widely dispersed teams throughout the width and depth of the battlespace, will require more flexibility in terms of access and understanding of information to cope with cognitive overload. In such a context, commanders at all levels and their staff will be simultaneously engaged in planning, synchronization and execution of operations. Based on the role and the task to conduct, each individual should have access to a customized view of the battlefield information.

ADO implies that the forces will behave as an agile organisation. Force agility has been studied in different works such as in Alberts and Hayes (2003) and Atkinson and Moffat (2005). This concept mainly refers to the capacity of maintaining an acceptable level of effectiveness in the face of changing circumstances. In their work, the North Atlantic Treaty Organization System and Analysis Studies, NATO SAS-085, has defined the concept of agility as the capability to successfully effect, cope with and/or exploit changes in circumstances SAS-085 (Aberts, 2011). Albert and Hayes (2003) talk about key dimensions of agility that are represented by the synergistic combination of the following six attributes: robustness, resilience, responsiveness, flexibility, innovation and adaptation.

In a context where agile forces have to plan, make decisions, and conduct tactical actions faster than what the enemy can respond or adapt to, the implementation of ADO will require the investigation and implementation of novel planning, collaboration and decision aids tools to enhance Land Force Command and Control Systems of the future to be responsive to the effects and expectations of the mission. An analysis of the information needed to plan and monitor missions led to the identification of four dimensions (DMR, 2011): Time, Space, Capability and Environment (Figure 1).

In fact, all plans may need to be viewed and evaluated from all of these dimensions. Furthermore, any modification done in one of these dimensions may have an impact on the other ones. This is why there is an intimate link between them. The capability to detect the impact that a modification on one of the dimensions has on the other ones as well as to be able to go from one dimension to another one became very useful. Such an approach has been proposed in (Allouche and Bélanger, 2013) and suggests new approaches for planning/monitoring support. This paper describes some concepts that can support some of these new approaches of decision aids for tactical planning and operation execution management, looking specifically at how we can develop more robust plans.

Robust planning accounts for modeling uncertainties, which include disturbing events that may significantly impact the tactical plan. The disturbances can be endogenous or exogenous (threats, environment) to the units involved in the tactical mission. By updating and propagating the uncertainty intervals as the mission unfolds, the planner is able to assess the robustness margin that remains and, to some extent, anticipate possible future issues and thus conduct some replanning. Working with time intervals instead of time instants makes the scheduling less sensitive to disturbances, which is expected to decrease workload, thus enabling humans to concentrate on crucial aspects of mission planning and execution.

The robustness approach implemented in the Tactical Planning and Execution Monitoring (TPEM) tool, developed at DRDC Valcartier, is based on the definition of constraints in the space, time, capability and environment domains depicted in Figure 1. This approach is presented in Section 3. An implementation of a tactical mission, entitled "Reconnaissance in Force Patrol" is presented in Section 4. Conclusion and future developments are provided in Section 5.

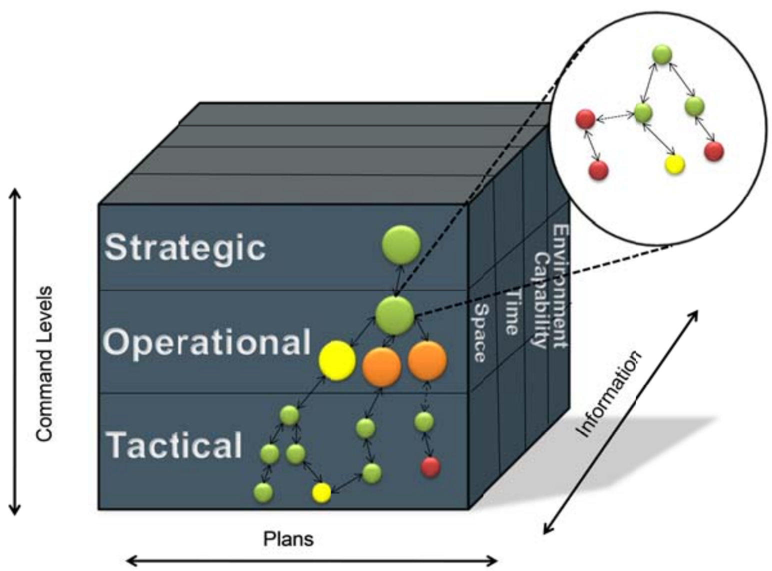


Figure 1: Information dimensions for planning and monitoring of ADOs

3. Constraint-based planning and monitoring

3.1. Motivation

The robustness of a plan is directly related to its ability to overcome minor deviations without replanning. One way to achieve this is to avoid constraints such as regulations and specifications that are not operationally relevant. To do so, reasoning based on sets rather than on single values is preferred. In the following sections we will elaborate on how constraint-based planning can help achieve plan robustness.

Military planning is carried out in multiple levels of detail on multiple levels of command. It is usually embedded in ongoing joint and combined operations and needs to respect the tactical situation with all of its various implications. All these aspects are in some ways adding constraints to the planning of the operation at hand.

These constraints can be subsumed as what we call the environment, as shown in Figure 2. The environment in this broad meaning is a source of constraints the plan needs to respect. These can be temporal constraints (e.g. arising from synchronizing with other operations), spatial constraints (e.g. due to the tactical coordination measures) or capability related constraints (most prominently the assets available for the current plan). On the other hand the actions planned will shape the environment and thus the constraints to further planning, adding or removing courses of action as discussed above.

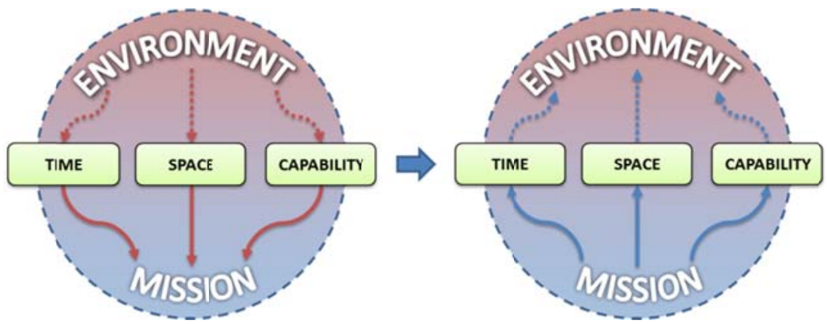


Figure 2: Constraint-based planning. The environment can be seen as a source of constraints in time, space, and capabilities for the mission at hand. In the same way the mission is influencing the environment in the domains time, space, and capability. This interdependent interaction is addressed in the concept of constraint-based planning.

Moreover, constraint-based planning helps to reduce the interaction of the user with the C2 system during execution of the plan. Constraint-based planning defines a set of solutions instead of selecting only a single solution; thus, a change of the plan is only necessary if the situation is changing the constraints in a way that all chosen solutions are ruled out completely. Small changes to the constraints like a short time delay or a slight change in capabilities available should not require any manual changes to the plan.

Military commanders naturally apply constraint-based planning. Thus, assessing the situation and all relevant constraints is key to any successful plan. So it seems only logical to apply this also to the C2 environment. While the large number of options and variables often may overwhelm human perception and thus usually one fixed plan is created in the analog environment, the possibilities of digital information processing could enable the commander to handle a complete set of trajectories to the desired end-state of the mission and thus to be more flexible and adaptable. Any gained flexibility especially supports dispersed operations, the main focus of TPEM.

In the next section, we present a system-theoretic framework that subsumes the proposed constraint-based planning currently implemented in TPEM. We stress the fact that (*i*) time-varying constraints shape the set of system state-space variables and decision variables that are, possibly non-unique, solutions to a planning problem, and that (*ii*) tactical missions involve dynamical systems, whether known or partially unknown, which typically interact over short time horizons.

3.2. Concept

A Mission can be defined as (*i*) a set of effect-based goals $G(x)$ to be achieved, (*ii*) a set of resources managed and exploited in a timely manner to reach the goals, (*iii*) blue force endogenous and exogenous constraints that must be satisfied, and (*iv*) information flow that enables situation awareness and decision making by networking dispersed resources.

The temporal evolution of constrained resources and effects characterizing a mission can, as suggested by the two-dimensional representation shown in Figure 3, be expressed as a set of state-space variables that is the solution of a constrained hybrid dynamical system (Aubin et al., 2011). Such a system, denoted (F, R), consists of the interaction of a continuous-time system F and an event-driven (discrete) system R.

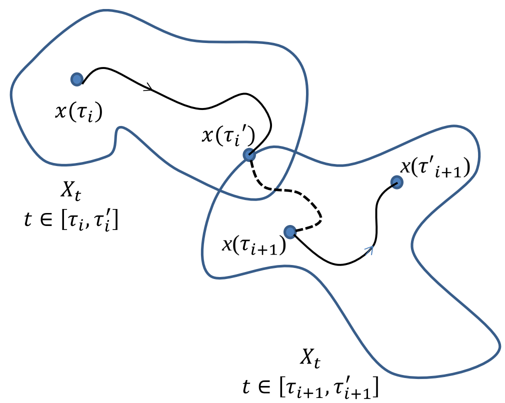


Figure 3: Two-dimensional representation of resources and effects time evolution. Time evolution of a mission states represented, for simplification purposes, as a two-dimensional hybrid dynamical system. Decision variables are not represented but follow a similar pattern. The run evolves as a sequence of time-continuous trajectories and jumps that may follow the occurrence of disturbance events. The time-dependent domain X_t is instantiated at two time instants each of which belongs to $[\tau_i, \tau_i']$, and $[\tau_{i+1}, \tau_{i+1}']$, respectively. An over-approximation of a constraint domain evolving over some interval $[\tau_i, \tau_i']$ would consist in considering a time-invariant domain set including the union of X_t obtained for every $t \in [\tau_i, \tau_i']$.

The continuous-time system is expressed with a time-parameterized differential inclusion

$$\dot{x} \in F_t(x),$$

for all $t > 0$, where the set-valued map F_t is defined by

$$\begin{gathered} F_t : X_t \rightsquigarrow Y \\ x \longmapsto y = f(t, x, u, e) \\ u \in U(t, x, e) \\ e \in E(t, x, e) \end{gathered}$$

X_t, U, Y, and E stand for the time-dependent state space domain, the control-command input space (i.e., the set of decision variables), the image space, and the disturbance space, respectively. E includes blue force endogenous and exogenous disturbances, such as endogenous blue force's fault/failures, and threats, respectively, which may impact the mission. Elements of E may be measurable, estimated, or potentially unknown. To simplify notations, the time variable t is omitted; that is, variables x, u, and e should normally read $x(t), u(t)$ and $e(t)$.

The planning process, defined by the mapping $(t, x, e) \longmapsto u \in \mathbb{R}^n$, where e is potentially unknown, includes scheduling, task assignment (e.g., weapon-target assignment), trajectory planning, and resource management. The multi-dimensional, time-varying signal u thus consists of vectors including such quantities as time constraints of tasks such as tasks end/start time intervals (temporal dimension), as detailed in Section 3.3, resources capacities (capability dimension), path waypoints (spatial dimension), task-resource-path assignment (capability dimension), and weapon-target assignment (not yet implemented). The environment dimension of TPEM may affect some of the constraints that are instrumental in defining X_t, U, Y, and E.

For instance, a subset χ of state vector x(t), where $\dot{x} \in F_t(x)$, may represent the position, orientation, health status (sensor, actuators, etc), and capability (e.g., available firepower, fuel, overall sensing capability) of ground and air vehicles at time *t.*

The event-driven system R is defined by a set-valued map

$$R_t : X_t \rightsquigarrow \phi,$$

which expresses how the mission state may abruptly evolve in response to the conjunction of stressors (e.g., actions of the enemy) and specific operating conditions. Such conditions include state-at-risk occurring when the mission state evolves near domain boundaries. Jump entailed by R can be expressed at time instant τ_i' by

$$x(\tau_{i+1}) \in R_{\tau_i'}\big(x(\tau_i')\big),$$

where

$$\begin{gathered} R_t : X_t \rightsquigarrow Y \\ x \longmapsto y = r(t, x, u, e) \\ u \in U(t, x, e) \\ e \in E(t, x, e) \end{gathered}$$

τ_i is an element of the hybrid time trajectory τ defined by

$$\begin{gathered} \tau = \{I_i\}, \\ I_i = [\tau_i, \tau_i'], i \in \mathbb{N}, \\ \tau_i \leq \tau_i' = \tau_{i+1}. \end{gathered}$$

Function r in R results from the occurrence at τ_i of disturbing events that may impact the mission by changing the resource state and forcing the planner to perform mission replanning. It should be noted that the definition of τ does not imply that jump time instants $\tau_i, i \in \mathbb{N}$, are known prior to the mission since their occurrences emerge from various uncertain processes that take place in a partially unknown environment.

The allowable state-input domain is thus defined by $X_t \times U(t,x,e) = C_{t,x,u}$. This set enforces the control policy output (e.g., scheduling and resource management) and the resource state to remain within time-evolving, event-triggered sets, noticing that the latter is dependent on the former through system (F, R).

Rather than being fully automated, the planning process is designed to facilitate rapid decision making that characterizes tactical level of operations. In doing so, human expertise is leveraged to seek viable solutions and courses of action to a goal achievement problem constrained by system (F, R). This means eliminating the inappropriate solutions from the overall input-state solution space thus obtaining a reduced solution space, yielding the following constraint

$$(u, x) \in C_{t,x,u}, \text{ for all } t > 0,$$

which expresses constraints on state variables x and decision variables u.

This approach is illustrated in Figure4. In the beginning, a set of viable solutions in some domain exists (depicted as green arrows) while all other solutions are ruled out by the existing constraints (illustrated as purple obstacles). During the course of events the constraints may change. This will remove some of the formerly valid solutions and possibly add new ones that were unavailable before.

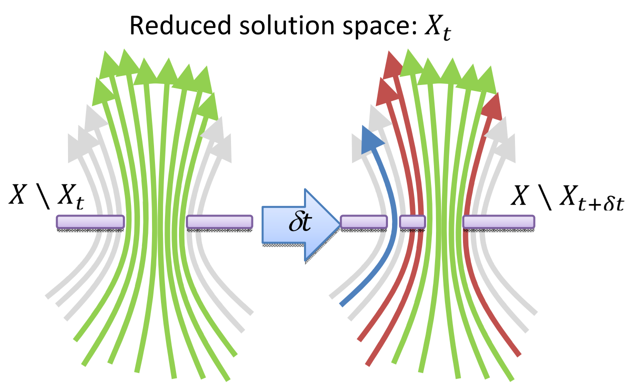


Figure4: The solution space Φcontains all thinkable courses of action in a given situation (here depicted as arrows). The reduced solution space Φ_t(green arrows) contains only such solutions that are not violating the current set C_t of constraints (here depicted as purple obstacles). While the situation evolves the constraints are changing. Thus after a timespan δt the reduced solution space has changed. Some solutions (depicted in red) are no longer available while others (depicted in blue) arise.

The reduced solution space contains all input-state solutions that do not exceed the boundary of the viability set. To find viable solutions, the constraint-based planning is simplified by decomposing the input-state domain$C_{t,x,u}$ in to the three subdomains presented in Section 3.1(i.e., space, time, resources), and seeking viable solutions in each of those constrained subdomains.

It is obvious that all changes in the constraints are of high interest for the planner as are the changes in the set of viable solutions. Thus our approach is to support the planner in the process of identifying the valid solution to his/her tasks by providing helpful information on all applicable constraints and on how these affect the current plan.

It should be noted that planning in each subdomain may be performed iteratively by reasons of couplings among the constraints expressed in every subdomain.

3.3. Time constraints: Robust scheduling

Robust scheduling is the goal of the TPEM approach to time constraints. In the time domain the limitations of crisp plans are the most obvious. As long as a schedule is represented inside the C2 system using exact time tables, it will need constant updates and will most likely require far too much user interaction during execution. For the same reasons synchronizing plans will become a tedious task, likely to end in extensive plan iterations.

Here the concept of a constraint-based schedule seems promising. In this approach tasks are not defined by crisp timestamps but use boundaries for beginning and ending of a task: the time constraints.

3.3.1. Principle

The basic principle of robust scheduling in TPEM was illustrated by Allouche and Boukhtouta (2009) and extended to fuzzy temporal planning in Allouche and Berger (2011). The approach uses the concept of temporal plans known as the simple temporal problem with binary constraints (M. Ghallab et al., 2004). It is based on a graph representation $\{A,T\}$ of the schedule (Figure 5(a)), where A denotes the set of action start-end nodes, and $T: A \times A \rightarrow I$, with I being the set of all integer intervals, defines temporal constraints between nodes. The expression of Allen's temporal relations (Allen, 1991), consisting of a set of logical connections between the individual tasks (e.g., task A equal, precedes, meets, start, finishes, or overlaps task B) and constraints to tasks where applicable (e.g. no longer than), can all be mapped into temporal constraints between actions.

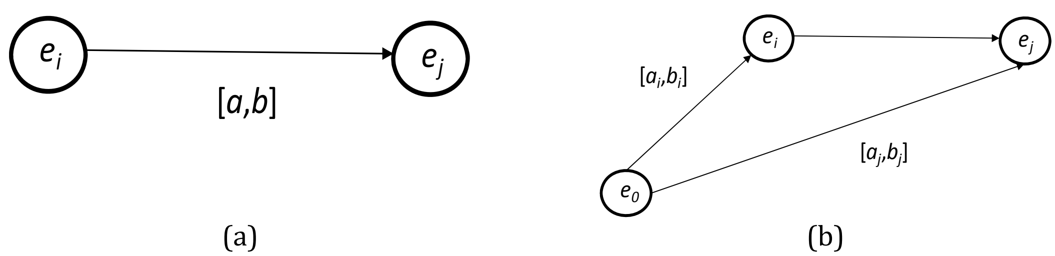


Figure 5: Temporal constraint between nodes.

Time intervals can be used to specify the set of all possible start/end time instants of a task, as shown in (Figure 5(b)). The time intervals are defined with respect to some reference node e_0. Using time intervals instead of time instants allows for carrying out robust scheduling of a mission by accounting for uncertainties in estimating the time duration of tasks.

A minimization operation is carried out on this graph (Allouche and Boukhtouta, 2009). The minimization has two outputs used in this approach: First, it only succeeds if the plan is valid, meaning it is logically consistent. Second, the resulting graph updates all time constraints such that every task (constrained and unconstrained) is displayed with the time constraints arising from the overall constraint schedule. This way each task is given an earliest and latest start/end time.

This minimization operation is also used when merging plans. The procedure will again only succeed if the plans can be synchronized and will display the updated earliest and latest start/end time that comply with the synchronized plan.

This enables the planner to create a schedule with a minimum of specific input needed. Basically only the logical connections of the individual tasks are required and the known time constraints are added. The use of subtasks allows for further details while delegation to lower command levels, naturally keeping track of the desired level of detail. Conflicts between operations can be identified as soon as time constraints are violated. Thus the approach allows for low-level synchronization and scalable granularity at the same time.

During execution the time constraints can be replaced by precise times; that is, actual task star/end times replace time constraints. New information is thus added to the robust schedule on the fly making it more precise by propagating and updating (minimization process) temporal constraints using the last available actual temporal constraints. As the mission unfolds, the length of task start/end time intervals tends to decrease, expressing the fact that the schedule temporal robustness shrinks as the time-to-mission-end approaches zero. The minimization process makes sure that conflicts in the schedule arising from the newly entered information are identified immediately.

3.3.2. Illustration

Figure 6 illustrates how tasks are displayed in the temporal view of TPEM. The mission is divided into its tasks (Figure 6(a)). Tasks themselves can consist of subtasks (Secure Route 1, FOB supplying and Secure Route 2 in Figure 6(a)-(b)), which again can be formed by further subtasks. This allows for a selective representation adjusted to the needed degree of granularity or to the level of command.

To indicate the time-dependencies, markers are used in the schedule representation (Figure 6(b)) illustrating the earliest and latest start or ending of each task. The temporal constraints defined for the mission are used to calculate all of these sections dynamically.

The graph representation of this plan is depicted in Figure 6(b). While it is not used in the user interface, this representation is useful for illustrating the process mentioned in section 3.3.1. This example depicts only three different node-to-node relations:

$[0,\infty]$ is the mathematical representation of the 'B at the same time or any time after A' relation and is therefore used for all subtask start and ending relations as there is no specific minimum or maximum duration postulated.

$[0,0]$ relates to 'A and B at the same time' and is used to connect end node and starting node of subsequent tasks in this example and also the mission start node with the start node of the first subtask assuming seamless connection of these tasks.

$[0,t_{max}]$ is used to represent a real temporal constraint on the overall mission reading 'B at the same time or no longer than t_{max} after A'.

To avoid a logical AND connection at the end of this plan the end node of the last subtask is connected to the end node of the mission via the $[0,\infty]$ relation. The lower constraint is 0 for all tasks as there is no finite minimum duration defined in this example (e.g. a minimum time to stay at a specific position).

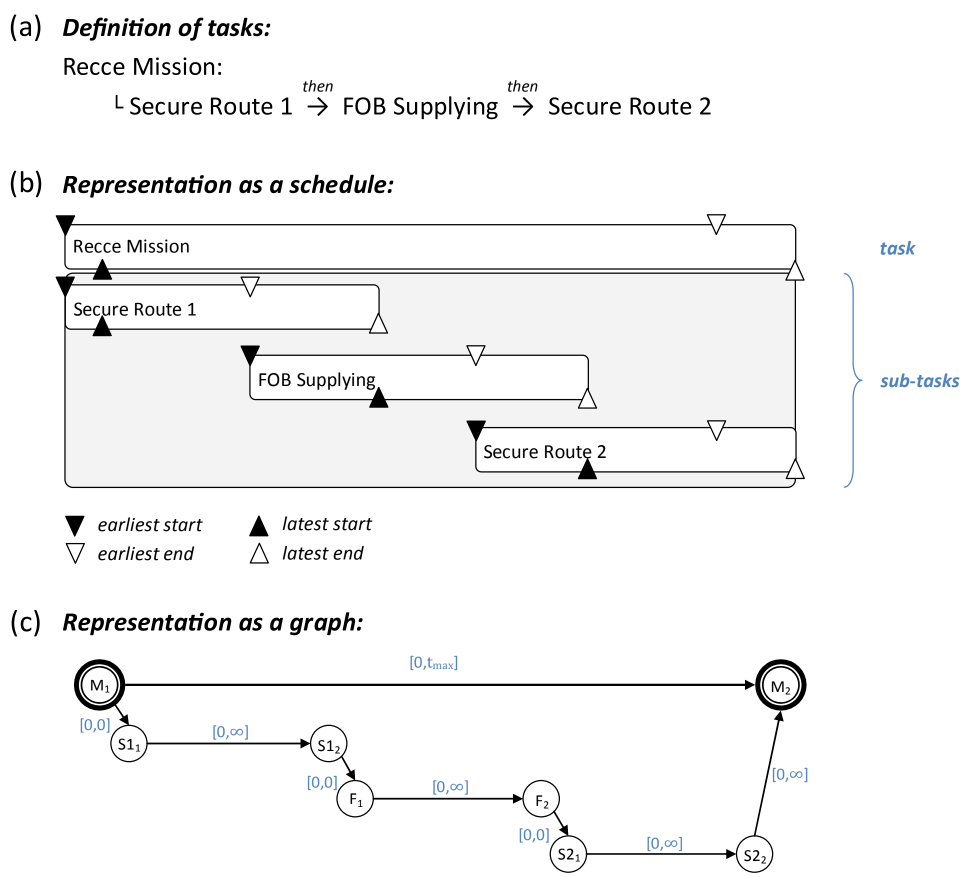


Figure 6: Schedule of a Mission using time constraints. Plans consist of tasks, and each task can consist of sub-tasks, thus reflecting the hierarchy of command. Crisp time constraints are used, defining earliest and latest start or ending of a task with respect to preceding and subsequent tasks.

This example already gives a hint that a relatively large set of different node connections arises from the limited number of temporal relations between tasks. These inter-node connections are automatically created from the task information entered. Then the minimization is carried out and only the resulting schedule is presented to the planner.

3.3.3. Execution mode

Two temporal task graphs are updated during the execution mode of TPEM: (*i*) The constraint-based graph used for robust scheduling (Figure 6(c)), where intervals represent task start/end time uncertainties; and (*ii*) a graph with time duration estimates of tasks.

Over the course of a mission, the information received from multiple sources (e.g., sensors, operators) is received and processed in real time by TPEM. The two graphs are updated accordingly. The time duration estimates are updated according to the mission assessment carried out by militaries involved in the mission execution. The propagation of time constraints is automatically testing whether the temporal constraint graphs remain consistent or not. Moreover, the two graphs are fused to verify that the updated time duration estimates remain consistent with the temporal constraint graph.

Notifications about temporal issues are thus sent whenever (*i*) a constraint is not satisfied, thus rendering the mission scheduled invalid, or whenever (*ii*) the updated time estimates do not comply with the temporal constraint graph. Monitoring the schedule changes as the mission unfolds remains impossible as long as graph inconsistencies are not cleared.

While TPEM functionalities such as what-if analysis, mission risk assessment, and optimal path planner remains to be further developed to better support mission replanning, several actions can be opted for to remove temporal inconsistencies. They include (*i*) shifting forward the upper bound of task time intervals, if no synchronization issues with other missions arise, (*ii*) speeding up tasks (e.g. tactical speed of units) while satisfying resource capability constraints, (*iii*) ignoring/delaying/splitting in time low-priority tasks, and (*iv*) spatial replanning in compliance with overall mission objectives and accepted risk level.

3.4. Spatial planning

While time constraints are only treated in one dimension the situation gets more complicated in space. The spatial representation of a tactical situation is a whole set of information in many dimensions. Also space is lacking the natural direction of evolution present in time. Nevertheless there are many ways to illustrate constraints in space. TPEM is currently implementing basic functionality to investigate the concept of spatial constraints in detail.

3.4.1. Approach

Typical tactical measures (e.g., area of responsibility) are utilized in TPEM as they represent the constraints in space defined by the operation. Zones and boundaries are particularly useful in this context.

Additionally TPEM uses an overlay-approach to present meta-data like frequency of hostile activities or the expected ethnical group of individuals encountered. Various mathematical concepts are examined, most prominently risk functions and the Delaunay triangulation with its complement the Voronoi diagram. The information is presented using an overlay that can be added to the tactical map. At the current state of implementation the information can be used as a reference during planning and execution. After examination of the concept more evolved techniques may follow, e.g. allowing for feedback on the time or capability representation of the plan.

3.4.2. Illustrative example

A typical question during the planning phase is what to expect, be it in terms of local reaction to the military presence or in terms of exposed risk to hostile action. In TPEM, this is covered by hotspot maps based on information on hostile events processed by the program.

Figure 7(a) shows such a map. The overlay is typically created for an area of interest. It is derived from the relevant events. The positions of the events for this example are added for clarity. For this overlay a risk function approach was used. The overlay depicts the assumed area of hostile activities while also giving an indication of the frequency of occurrence. It can be used for instance to support path planning, choice of capabilities, or scheduling.

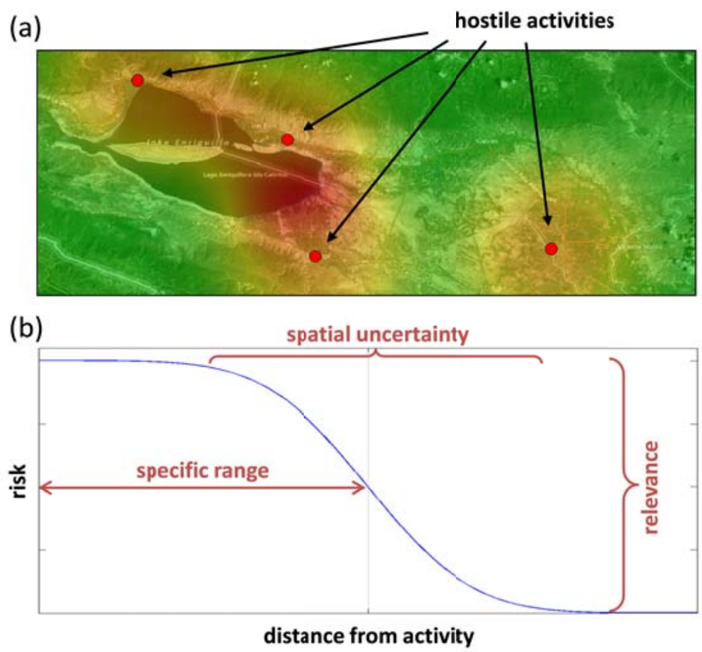


Figure 7: Hotspot map based on a risk function approach. A set of hostile activities is used for the calculation of the hostility level determined over the discretized area of operation. This map can be used as a constraint when planning or monitoring a mission.

Figure 7(b) depicts the utilized risk function. The error function was chosen due to its direct relation to the Gaussian distribution and stochastic calculations. Three variables of the complementary error function are used to characterize a hostile activity. The specific range describes the estimated area of operation surrounding the reported position of a single event. The spatial uncertainty value defines the transition to zero at the boundary of the estimated area of operation and is related to the variance of the corresponding distribution function. Finally the relevance value can be used to scale the intensity of events. The resulting risk values at a given position in space are summated for all contributing activities. Other aggregation operators could be implemented depending on the type of threats and the interpretation attached to the concept of hostility.

For instance, the probability p_M to be attacked at a given place P, as a result of the presence of armed threats i modelled with probability p_i to operate at P, can be computed using probability calculus, resulting in $p_P = 1 - \prod_i (1 - p_i)$.

Several other methods are investigated to exploit additional social or tactical information including social interaction map based on Voronoi diagrams and threat maps based on Delaunay triangulation and neighborhood analysis. Like the hotspot map in Figure 7, the resulting overlays could be used as a planning tool or to judge situations during the execution phase of a plan.

3.4.3. Planning with zones

The concept of zones is instrumental in performing constraint-based spatial planning. Each zone is characterized by attributes and rules. Zone attributes include type of zone (e.g., area of operation, area of influence, area of interest), associated mission, organization as well as strategic resource moving in the area, and key geographical data. Zone location may evolve in time. Simple rules expressing topological properties among zones, paths, and events allow solving conflicts and monitoring events that are critical to the mission success.

When zones and hotspot maps are available, the planner provides waypoints, checkpoints, and waiting areas that define primary routes and deviation routes. While not yet implemented, automatic path planning and generation in hazardous environments is deemed possible in TPEM by linking Scipio/Optipath tool, developed by DRDC Valcartier (Pigeon et al., 2009), to TPEM.

In execution mode, a notification is sent whenever a rule is not satisfied. The purpose of sending notifications, whether in the spatial or temporal domains, is twofold: (*i*) alert the planner that the occurrence of a conflict (e.g., resource-task assignment), a constraint violation, or a rule violation has been detected; and (*ii*) assess the extent to which the actual mission course of actions deviates from that of the plan.

3.5. Resource planning

The management of resources used to conduct a tactical mission is carried out by relating them to schedule tasks and corresponding objects in the spatial domain, as further illustrated in Section 4. First, a list of capability requirements is assigned to each task of the schedule. Similar to the temporal constraints, the capability requirements are part the command-control input signal domain, $U(t, x, e)$, defined in Section 3.2, and can thus be interpreted as constraints on planning and execution. Capability constraint satisfaction reflects the availability and allocation of resources for the mission planning and execution.

Whether in planning or in execution mode, a notification is sent whenever a capability constraint is not satisfied or a resource is lost or misused.

When the set of primary and deviation routes along with actions, the corresponding robust task graph, and resources and capacities are defined, the planner iterates so that every constraint is satisfied. The three domains objects are functionally related; that is, modifying the command-control input signal $u \in U$ will impact the entire state x. For instance, given a set of routes, increasing unit tactical speed, while meeting resource capacity, may help remain within the schedule boundaries, should a major event occur. In other circumstances, deriving a plan by seeking a solution that concurrently exploits every dimension of the input space U (i.e., spatial, temporal, and capability domains) is necessary.

3.6. Environment

The environment domain shown in Figure 1 stores the information that complements that included in the temporal, spatial, and capability domains. The environment is interpreted as a constant source of constraints whether in mission planning or monitoring of mission execution. For mission planning, this domain serves as a repository for intelligence summary, mission statements and orders, and weather forecast, which are uploaded until the mission starts since they may evolve in time.

Via a messaging and knowledge sharing service as well as by providing context related information from internal and external sources the planner will be enabled to identify constraining elements that affect the current plan.

For mission execution, the environment view represents the gateway for sending and receiving information. The current implementation includes messaging services and web browser functionality. The real-time reception of information obtained from various sensors (GPS location) and blue entities (operators, other missions' commanders, intelligence cell) by means of communication sensors is subsumed under the environment view. The information representation is structured by adopting military reports typically used in missions. For instance, the experiments presented in Section 4 include such reports as situation reports, contact report, IED contact reports, and medical evacuation.

Additionally a widget concept supports the implementation of further utility features like weather information. The majority of user interaction with network capabilities will be joined in the environment view.

4. Demonstration: Reconnaissance in force patrol mission

4.1. Context

The concept presented in Section 3 is illustrated by implementing a tactical mission, namely a Reconnaissance in Force Patrol. A tactical mission planning is conducted in TPEM from the information included in a Company Combat team order and Battle group orders (CAE, 2014). All those orders have been derived following a typical chain of commands, from the Land Component Plan and the Concept of Operation to Operation orders, including Brigade orders and intelligence report (CAE, 2014).

In this fictitious scenario, the A Company Cbt Tm will have to clear two routes, namely

DIAMOND and BEAR Routes, to ensure unimpeded military and humanitarian operations along these routes. There are a number of critical points to check, and halts to be conducted. A logistic operation is carried out at the B Company forward operating base. The combat team consists of eight units. An unmanned aerial vehicle is available for surveillance.

Platoon-sized elements of the Peoples Liberation Army are operating along DIAMOND Route and it is assessed that they are capable of blocking DIAMOND Route. They have been known to use IEDs and block the roads with hasty check points.

4.2. Planning

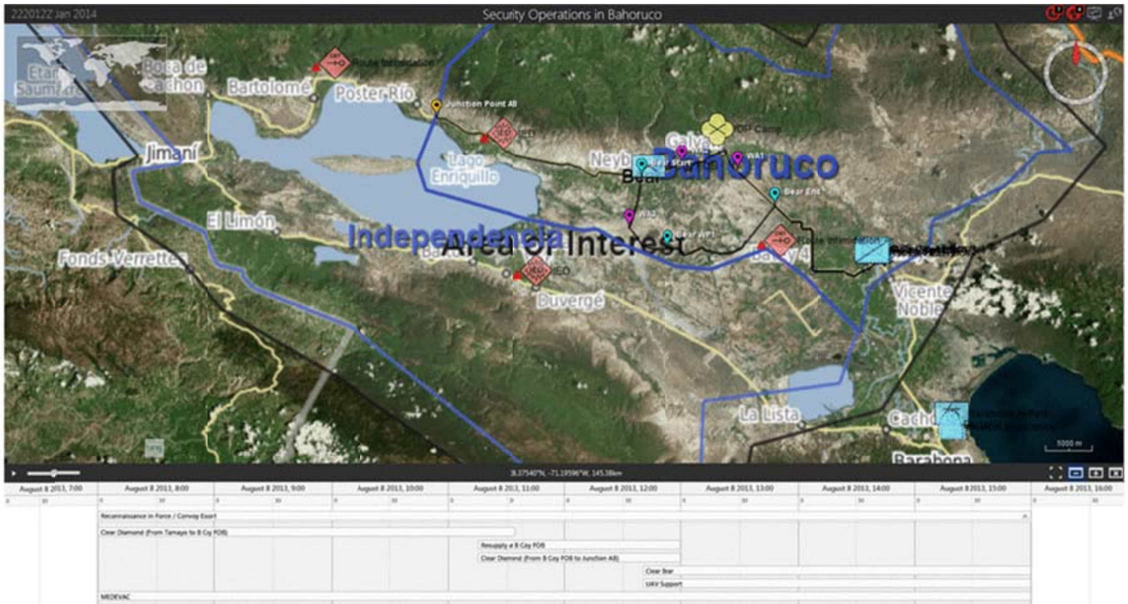
The four views depicted in Figure 8 to Figure 12 provide the information usually found in a synchronization matrix, where time schedule, assigned resources, and spatial information are provided in a single document. The planning process is started by defining the mission tasks and the temporal constraints among them. Precedence constraints as well as time intervals are defined when the information is available. If the temporal information is not available unbounded intervals are used, where appropriate. However, owing to functional links established between domains, the information captured in the capability and spatial views may help define temporal constraints such as time duration estimates of tasks; for instance, the knowledge of the convoy's tactical speed and route length results in the computation of the corresponding task duration estimate.

(a)

(b)

Figure 8: Temporal view. The schedule consists of several tasks that are related by precedence constraints. Time intervals are also used to specify uncertainties on task start/end times. The mission end is delayed by one hour in (b), with respect to the schedule in (a), to increase start/start time margins of Clear route task, which is deemed high risk. Notification mechanisms, displayed by red triangles, are implemented to advise the planner of conflict occurrence. In this example shown above, conflicts on resource-task assignment have to be solved.

Objects of interest, including areas, zones, threats, resources, internally displaced person camp, and bases are defined and geo-referenced. Objects are linked to tasks in the temporal view, which can also be displayed in the spatial view, as shown in Figure 9(a). The hotspot map (Figure 10) may be exploited as a support for route planning as well as for capability and resource assignment, depending on risk level along the route candidates.



(a)

(b)

Figure 9: Spatial view. Two areas of operation are displayed. A Coy combat team conduct a tactical and supply mission in Bahoruco area along Diamond and Bear Route. Standard 2525 symbols are used to represent camps, resources, and threats. Several spatial objects are related to the tasks in the temporal view, which can be displayed (a) or not (b) in the spatial view.

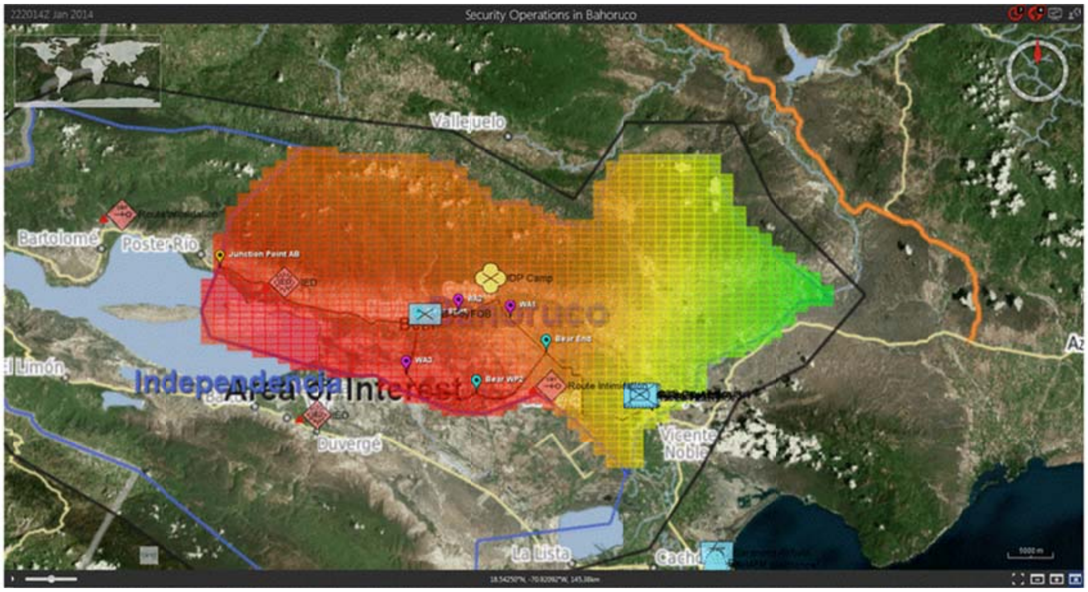


Figure 10: Spatial view with hotspot map. This map is derived from the knowledge of red threat positions, provided by the intelligent summary.

When moving along a high-risk road is mandatory, the tactical mission overall risk can be mitigated by modifying the requirements defined in the capability view, as shown in Figure 11. To do so, operational parameters of interest include speed limits, types of vehicles, level of protection and firepower.

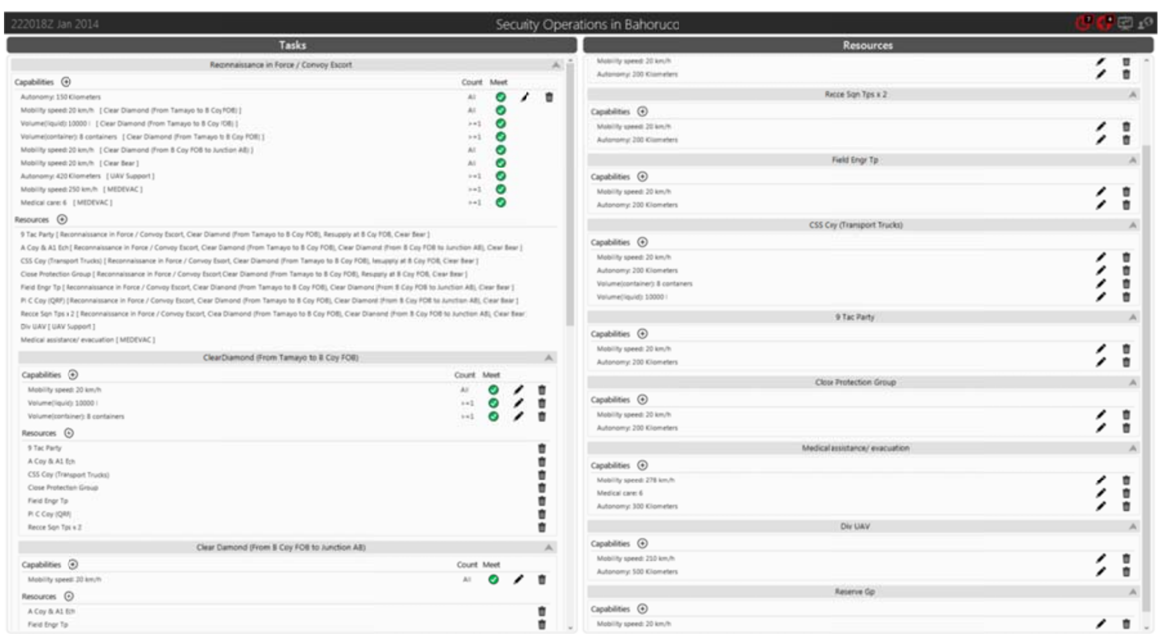


Figure 11: Capability view. The capability requirements (left-half part) are defined for every task of the schedule. Resources, which must satisfy the requirements, are defined in the right-half part of the screen. Notifications about requirement satisfaction are provided in the task part of the view. A green pictogram indicates that a requirement is met by the proposed resource.

Also not yet implemented, the integration of a move planner into TPEM as a computation tool combined to the capability view, as suggested in Section 5, might support the planner in better understanding dependencies between control-command input and state variable. For instance, risk mitigation by increased level of protection and fire power tends to increase the weight of vehicles, which in turn decreases the tactical speed, and impact task start/end time estimates.

The environment view shown in Figure 12allows displaying and sharing information from/to the TPEM environment. Pre-mission reports, current mission reports, weather reports, and raw or processed sensory data (e.g., GPS location, surveillance data) are displayed in this view.

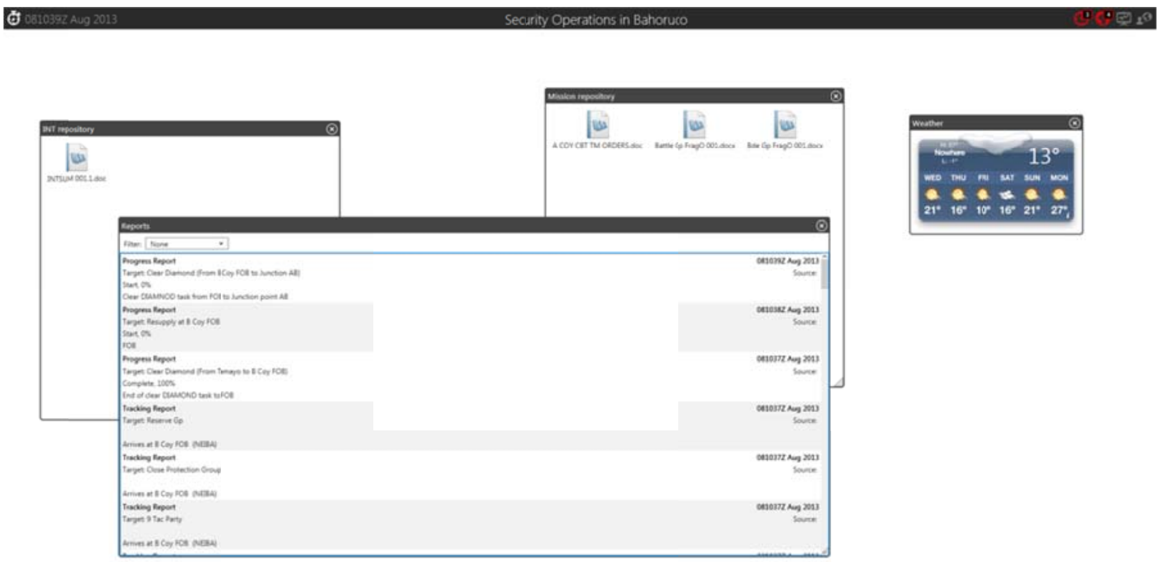


Figure 12: Environment view. Intelligence reports as well as orders from several levels can be found in the information repositories of this view. Weather forecast and reports windows allow displaying time-evolving information. The reports window show all the military reports (SITREP, ContactREP, INTREP, etc) that are sent over the course of the mission. They can be displayed using filters to easily retrieve a specific type of report.

4.3. Emulation of mission execution for monitoring

The TPEM prototype, which is currently implemented on a tablet-like hardware, is expected to be connected to a variety of sources of data including humans and sensors. Communication networks and touch screen will serve as a means for receiving and sending data from/to TPEM. The current version of TPEM allows information sharing only from the planner using the touch screen of the tablet; therefore, all other sources of data are emulated by means of a stimulator, which is an XML file that sends, at different time instants, various reports that contain the information that a communication network would have actually broadcasted. Reports thus have the ability to modify the status of TPEM objects or to create new objects. For instance, a tracking report modifies the coordinates of an object in the spatial view, whereas a progress report indicates whether or not a task has started or is completed, as well as the level of completion of ongoing tasks. Status reports provide information about the availability of a resource and its health status. Mission reports are textual reports such as situation reports, intelligence reports, contact reports, and medical evacuation orders. When a situation report indicates the occurrence of an unexpected event (IED detonation, ambush, incident), a new object is generated in the spatial view.

As the mission unfolds, the mission state evolves in time and is communicated in discrete time to each view. Each task start and task end triggers the update of the time schedule and the possible display of notifications, should temporal graph inconsistencies, capability constraint violations, or task-resource management conflicts arise (see Figure 8).

The spatial view can display the schedule found in the temporal view, as shown in Figure 9(a). When this option is selected, the operator can simulate the time evolution of the combat team along the routes by moving a temporal cursor over a time window $[t, t+T)$, for some $T>0$, where t represents the current time. Assuming that the tactical moving speed pattern is known over $[t, t+T)$, the unit position is predicted over this time interval from the last available unit states (position, health status) provided by sensors. Depending on the state reached at $t+T$, mission replanning is conducted or not.

5. Conclusion and future work

Initial indications are that the current version of TPEM tends to show flexibility in planning and monitoring missions with temporal uncertainties. Central to TPEM is the robust planning based on relative time constraints and time interval propagation. Robustness aims to prevent TPEM operator from systematic replanning when moderate disturbances affect the plan. Feedback from recent demonstrations suggests that the tool might be flexible enough for planning at different echelons provided the appropriate information is exploited by removing extraneous details from higher level orders and adding details that are pertinent to conducting the mission. Future work could involve more detailed analysis of results of experimentation.

The prototype could be improved in numerous ways. Tools that are currently used by mission planners such as the move planner could be easily integrated to TPEM. For example, the move planner, which computes the tactical speed of units, inter-units distances, and waypoint transit times based on convoy/sub-units specifications, could seamlessly be integrated to the capability view with resulting timings sent to the temporal view.

Spatial reasoning approaches are to be investigated to develop functionalities for robust spatial planning that would be similar to the robust scheduling presented in Section 3.3. In so doing, constraint satisfaction in the temporal, spatial and capability domains would be fully integrated.

Support for temporal view replanning when in conflict with temporal constraints is currently being investigated to reduce human interaction further where possible, and should account for a risk-effort-benefit trade-off analysis.

Enabling adaptive dispersed operations would require developing and integrating network-related tools (hardware, software, algorithms) to permit data communication among mission units and to conduct distributed planning and mission execution monitoring.

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