Defence Research and Development Canada
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RAP compilation and exploitation for dynamic operations management

Review of 13dy activities

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Defence Research and Development Canada – Valcartier

Technical Report
DRDC Valcartier TR 2010-332
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IMPORTANT INFORMATIVE STATEMENTS

Abstract

This close-out report of the project 13dy "RAP Compilation and Exploitation for Dynamic Operations Management" identifies the documents that were published to describe the concepts investigated during the execution of this project. These concepts include:

- Real-time gathering of missing information about the area of operations;
- A framework supporting the situation analysis; and
- Integration of plans in the global understanding of the situation.

Résumé

Ce rapport synthèse du projet 13dy « Compilation et exploitation d'une image opérationnelle aérienne pour la gestion dynamique des opérations » identifie les documents qui ont été publiés pour décrire les concepts étudiés dans ce projet. Ces concepts incluent:

- La saisie en temps réel d'informations manquantes sur la zone d'opération;
- Un cadre de travail pour l'analyse de situation; et
- L'intégration des plans dans la compréhension globale de la situation.

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Executive summary

RAP compilation and exploitation for dynamic operations management

Micheline Bélange; DRDC Valcartier TM 2010-332; Defence R&D Canada – Valcartier; June 2011.

Situation awareness, a state of mind in a human, concerns the perception of the elements in the environment, the comprehension of their meaning, and the projection of their status in the near future. Different tools can be used to support the development of situation awareness. The Air Picture is one of them. Accordingly, a good compilation of the Air Picture leading to a sound understanding of the situation as well as a reliable projection of what may happen in the future necessitates efficient management of air events in context. This involves the ability to detect events based on the Common Tactical Picture, to identify the significance of those events, as well as to determine and understand the relationships between the events. The context includes environment; infrastructure; blue, red, brown and white pictures; air corridors; air operations and operations dependencies.

Project 13dy, named "RAP Compilation and Exploitation for Dynamic Operations Management", was conducted to investigate some of the enablers that would lead to the development of situation understanding considering that this state of mind should support the planning and execution of specific operations. This close-out report of the project 13dy identifies the 23 documents that were published to describe the concepts investigated during the execution of this project. These concepts include:

- Real-time gathering of missing information about the area of operations;
- A framework supporting the situation analysis; and
- Integration of plans in the global understanding of the situation.

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RAP compilation and exploitation for dynamic operations management

Micheline Bélanger; DRDC Valcartier TM 2010-332; R & D pour la défense Canada – Valcartier; Juin 2011.

La connaissance de la situation, un état d'esprit de l'humain, est liée à la perception des éléments de l'environnement, la compréhension de leur sens et la projection de leur statut dans un futur immédiat. Différents outils peuvent être utilisés pour appuyer le développement de la connaissance de la situation. L'image aérienne est l'un d'eux. Ainsi, une bonne compilation de l'image aérienne menant à une compréhension de la situation, ainsi qu'à une projection fiable de ce qui va arriver dans le futur nécessitera une gestion efficace des événements aériens dans le contexte. Cela implique la capacité de détecter des événements basée sur l'image tactique commune, d'identifier la signification des événements, de déterminer et de comprendre les relations entre ces événements. Le contexte inclut l'environnement, l'infrastructure, les images bleues, rouges, brunes et blanches, les corridors aériens, les opérations aériennes et les dépendances entre ces opérations.

Le projet 13dy - « Compilation et exploitation d'une image opérationnelle aérienne pour la gestion dynamique des opérations » - avait pour but d'étudier les concepts initiateurs qui permettront de développer la compréhension de la situation compte tenu que cet état d'esprit devrait appuyer la planification et l'exécution d'opérations. Ce rapport synthèse du projet 13dy identifie les 23 documents qui ont été publiés pour décrire les concepts étudiés dans ce projet. Ces concepts incluent:

- La saisie en temps réel d'informations manquantes sur la zone d'opération;
- Un cadre de travail pour l'analyse de situation; et
- L'intégration des plans dans la compréhension globale de la situation.

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1 Introduction

It was confirmed in a previous work [1] that the concept of Recognized Air Picture (RAP) was not properly defined, leading to different interpretations of what it should or should not include. From that study, it was quite clear that the concept of RAP could not be limited to the knowledge obtained from track information. Situation awareness (SA), a state of mind in a human, concerns the perception of the elements in the environment, the comprehension of their meaning, and the projection of their status in the near future. Different tools can be used to support the development of SA. The Air Picture is one of them. Accordingly, a good compilation of the Air Picture leading to a sound understanding of the situation as well as a reliable projection of what may happen in the future necessitates efficient management of air events in context. This involves the ability to detect events based on the Common Tactical Picture, to identify the significance of those events, and to determine and understand the relationships between the events. The context includes environment; infrastructure; blue, red, brown and white pictures; air corridors; air operations and operations dependencies.

While the RAP should include information to aid detection, identification and tracking of air assets, it should also provide all information and knowledge that will permit timely operational and strategic decision-making for all Canadian Air Force headquarters and higher headquarters. In the previous study, a list of aspects requiring investigation to support RAP compilation and exploitation was identified. This list included aspects of:

- Identification of the types of information that could improve SA (RAP enablers);
- Information gathering strategies required to compile an air picture;
- Identification of dynamic resource planning models and algorithms for near real-time and real-time information collection (collection management enablers);
- Dynamic change detection and relationship discovery techniques;
- Situation and event recognition system requirements;
- Forecasting and prediction techniques;
- Intelligent adaptive interface investigation;
- Visualization techniques investigation (e.g., to represent dynamic relationships, etc.);
- Experimentation on the level of support that a RAP display can provide for a common and shared mental model of the air battlefield;
- User interface guidelines for RAP display.
- Approaches/strategies/techniques for dynamic air operations planning and management;
- Approaches/strategies/techniques for real-time mission execution and feed-back;
- Approaches/strategies/techniques to provide real-time airspace deconfliction capabilities;
- Plan representation investigation;
- Plan simulation investigation;

- Plan forecasting approaches investigation;
- What-if analysis approaches investigation.

Project 13dy, named "RAP Compilation and Exploitation for Dynamic Operations Management", was conducted to investigate some of the different enablers that would lead to the development of situation understanding considering that this state of mind should support the planning and execution of specific operations. In order to develop and demonstrate the concepts related to the development of SA appropriate to the Air Force, a vignette of Combat Search and Rescue (CSAR) [2] was developed, considering that it involves many different types of operations , such as:

- Surveillance of a specific area, including RAP compilation and mission planning, monitoring and control to improve surveillance;
- Target detection, which includes planning, monitoring and control of missions to improve the search;
- Recovery, which includes planning, monitoring and control of missions to recover the target.

Since CSAR operations take place in hostile territory, they provide the level of complexity and the time constraints needed to demonstrate our concepts for the compilation and exploitation of the RAP while dealing with an operation of suitable scale.

This report, which constitutes the close-out report of the project, presents the different concepts that were investigated during the project. This is done through the presentation of the reports and articles that were published. Section 2 presents the concepts that support real-time gathering of missing information leading to situation understanding; Section 3, a framework supporting the situation analysis; and Section 4, the concepts to integrate our own plans in the global understanding of the situation.

2 Approaches to gathering information required to understand the situation

Understanding the situation in an area of operations is essential for the execution of an operation. However, the existing sensor infrastructure may not adequately cover the area concerned. To compensate, mobile sensor resources can be reallocated to provide the information needed to develop the SA of a specific area of operations. This section presents the four aspects of the problem that have been investigated:

- Cooperative search path planning;
- Dynamic distributed patrolling;
- Dynamic vehicle routing;
- Visibility-based terrain analysis for route planning.

2.1 Cooperative search path planning

To bridge the gap between information need and information gathering, swarms of unmanned aerial vehicles (UAVs) can provide more “eyes” out in the field. The concepts of multiagents, distributed continual planning and co-evolution for path planning were investigated for search and reconnaissance problems. The following papers describe the work that has been conducted in this area.

1. Happe, J., Yates, R., Berger, J. Making UAVs learn to cooperate in military ISR, UVS Canada Montebello 2006, Conference, Nov 6-10, 2006, Montebello, Quebec. [3]

> High-level mission planning for swarms of UAVs in military Intelligence, Surveillance and Reconnaissance comes with novel challenges. As a case study, we consider distributed search and identification of targets in a battlefield scenario. This is a difficult problem because of 1. the high problem dimensionality introduced by multiple UAVs, 2. the scarcity of resources, particularly time and computing power, 3. the high amount of uncertainty about the environment and about an enemy's intentions, 4. the limited availability and reliability of communication, and 5. a dynamically evolving situation.
>
> In this talk, we identify four principles for addressing these challenges and developing workable solutions. First, we advocate Artificial Intelligence approaches to planning, augmented by recent techniques to handle uncertain and dynamic situations. Second, the high dimensionality of the problem requires a decomposition of the problem into smaller sub-problems. Third, we advocate autonomous and cooperative control of

UAVs, as opposed to central or hierarchical control. Finally, the high dynamicity of the situation requires continual real-time adjustment of plans.

In our approach, UAVs form teams to execute tasks. Communication between teams is limited to the exchange of tasks, bids, and acknowledgements. Target search is characterized as information gain over a probabilistic search map, with the objective of reducing entropy. UAVs bid for tasks using an auction mechanism whose goal is to attain a Nash equilibrium. The research includes development of a simulation package to test our algorithms. This research project is done for, and in cooperation with, DRDC Valcartier, Quebec.

2. Happe, J., Distributed Continual Planning in military ISR - RAP/CE Literature Survey, CR 2006-708, December 2006. [4]

This document reports on an extensive study of the academic research literature on Distributed Continual Planning for Unmanned Aerial Vehicles (UAVs) in the military ISR (Intelligence, Surveillance, Reconnaissance) domain. This is a very active area with a large number of recent contributions. The goal of the study is to provide a comprehensive picture of the state of the art in the field, and to find key contributions, limitations, and interesting challenges for future work. Based on these findings, we make recommendations for follow-up research.

The Distributed Continual Planning problem is hard because of 1. the high problem dimensionality introduced by multiple UAVs, 2. the scarcity of resources, particularly time and computing power, 3. the high amount of uncertainty about the environment and about an enemy's intentions, 4. the limited availability and reliability of communication, and 5. a dynamically evolving situation.

We present an abstract mathematical formulation of the problem and demonstrate how different ideas such as data fusion and resource management, inter-agent coordination, information gathering and task allocation fit in this setting. We characterize how the different problem dimensions (platforms, environment, targets, threats, humans in the loop, sources of uncertainty) contribute to the hardness of the problem. We advocate a hierarchical decomposition into four levels of abstraction: team formation, task allocation, path planning and airspace deconfliction. (Lower levels such as obstacle avoidance and sensor/actuator control are beyond the scope of this survey.)

A large section of this document is devoted to a study of approaches in the literature. We present these approaches along the above abstraction levels, including hybrid approaches, which address the coupling between subproblems at two levels. The study covers contributions in Control Theory, Operations Research and Artificial Intelligence. It covers the whole spectrum between "classical" (e.g. Search Theory) and modern fields (Evidence Theory, Mechanism Designs, Co-Evolution, Knowledge Representation etc.).

Our document concludes with an outline of open problem classes and promising research directions, motivated by the limitations and future work identified in the literature. We also make recommendations for algorithm design and implementation, identifying a suitable approach for each level of abstraction and suggesting an architecture that naturally supports distributed computation and platform cooperation.

3. Happe, J., Cooperative Path Planning and Information Sharing in the Context of a Recognized Air Picture – Architecture Guide, November 2008. [5]

The objective of the work documented in this report is to investigate advanced technology concepts for learning multiagent coordination within the context of a distributed information gathering problem: cooperative target search.

The growing interest in developing automated network-enabled decision support capabilities for command, control, communication, computer, intelligence, surveillance and reconnaissance (C4ISR) poses the problem of dynamic distributed resource management and demands information sharing, shared understanding, agility and synchronization solution concepts. This is exacerbated by the ever-increasing pervasiveness of recent and cheap technologies, particularly the deployment of unmanned aerial vehicles (UAVs) in larger and larger numbers throughout military/civilian ISR activities.

This project focuses on the development of new advanced technology concepts (e.g. framework, algorithms) and automated advisory decision support capabilities for dynamic distributed resource management (distributed continual planning). In that setting, a heterogeneous group of agents (from distinct classes of ISR assets) performs a joint target search and surveillance mission in a dynamic uncertain environment with both known and unknown targets, as well as threats. The agents may be human and/or computational, and show cooperative, non-coooperative (self-interested) or mixed behaviours/attitudes. The agents face constraints regarding sensor capabilities, as well as communication range and bandwidth. Learning coordination in order to optimize joint task solutions and communication under these constraints, trading-off solution quality and effort (cost or run-time) are the essential elements addressed here.

The goal of this work is to show the value of the Recognized Air Picture (RAP) in a Combat Search And Rescue (CSAR) military application domain. New technology concepts such as learning multiagent coordination algorithms and intelligent assistants are aimed at improving distributed resource management and bridging the gap between information need and information gathering (and response management), in a tactical dynamic uncertain environment. The findings are applicable and exploitable in a variety of military and civilian application domains.

This report is one of four reports documenting the outputs of this work. It proposes a novel approach and solution architecture, applying genetic algorithms and multi-agent coevolution path planning to the cooperative target search problem. It further proposes a novel concept for information sharing, which takes communication constraints into consideration and contributes towards the above-mentioned trade-off between solution quality and effort. The work is built upon and significantly extends the work performed in the RAP Compilation./Exploitation (RAP/CE) project.

4. Berger, J., Happe, H., Gagné, C., Lau, M. Co-evolutionary Information Gathering for a Cooperative Unmanned Aerial Vehicle Team, 12th International Conference on Information Fusion 2009, Seattle, Washington, USA, 6-9 July 2009. [6]

   Persistent surveillance and reconnaissance tasks in mobile cooperative sensor networks are key to constructing recognized domain pictures over a variety of civilian and military problem instances. However, efficient information gathering for a task such as target search by a team of autonomous unmanned aerial vehicles (UAVs) still remains a major challenge to achieve system-wide performance objective. Given problem complexity, most proposed distributed target search solutions so far consider simplifying assumptions such as predetermined path planning coordination strategy with implicit communication and ad hoc heuristics, and severely constrained resources. In this paper, we extend previous work reported on multi-UAV target search by learning resource-bounded multi-agent coordination, involving explicit action control coordination. The approach first relies on a new information-theoretic co-evolutionary algorithm to solve cooperative search path planning over receding horizons, providing agents with mutually adaptive and selforganizing behavior. The anytime algorithm is coupled to an extended information-sharing policy to periodically exchange world-state information and projected agent intents. Preliminary results show the value of the proposed approach in comparison to existing techniques or methods.

2.2 Dynamic distributed patrolling

Sometimes, we need to be able to provide regular information on specific targets. Autonomous UAVs could be used to execute this type of information gathering. If a team of autonomous UAVs must coordinate to patrol moving targets over a large area, then we have a dynamic distributed patrolling problem. The problem is to automatically find patrolling patterns in a dynamic environment characterized by unknown obstacles and moving targets. The challenge is to solve such a problem taking into account the geographic characteristics of the environment and the fact that targets may move in an unpredictable manner. This section presents the work that was done to investigate reinforcement learning techniques to propose near-real time dynamic distributed patrolling solutions that can take into account the preferences of the decision-makers.

5. Perron, J., Hogan, J., Investigation of MUSCAMAGS for Distributed Continual Planning – Tactical Surveillance and Reconnaissance – Investigation of critiquing systems into the continual planning tool COLMAS. DRDC Valcartier CR 2006-594, September 2006. [7]

    This document proposes an architecture supporting a cooperation process between a human and a computer to allow designing successful UAVs cooperative problem-solving systems for the surveillance task. This Computer-Supported Cooperative Work system architecture is based on 5 processes : a Machine Learning (ML) process which generates solutions, an evaluation process which evaluates solutions, a critiquing process which produces comparative critiques of solutions, a refining process which extracts implicit knowledge from a user to automatically adjust the ML process and a validation process which validates the user's knowledge coherence according to the military doctrine, lessons learned and previous solutions.

6. Vrljicak, T., Perron, J., Hogan J., Investigation of MUSCAMAGS for Distributed Continual Planning – Tactical Surveillance and Reconnaissance - Literature review, DRDC Valcartier CR 2006-602, November 2006. [8]

    The objective of this paper is to give some issues and references in order to guide readers to use a reinforcement learning approach to solve the surveillance/patrolling task. To achieve this, chapter 2 presents the reinforcement learning area which can handle cooperative and dynamic problem (Markov Decision Process (MDP), Partially Observable Markov Decision Processes (POMDP) and Game theory). Afterward, chapter 3 presents some actual research, susceptible to be relevant for the problem to solve in a complex and dynamic scenario. Chapter 4 focuses on limitations and interesting open topics in the field of cooperative multi-agent reinforcement learning in the context of a real world application.

7. Perron, J., Hogan, J., COLMAS Project – Technical Survey and COLMAS architecture, DRDC Valcartier CR 2006-601, December 2006. [9]

   This project intends to develop frameworks, algorithms, and automated advisory decision support capabilities for dynamic distributed resource management in which a heterogeneous group of UAVs are engaged in a surveillance mission. This mission evolves in a dynamic uncertain environment with both known and unknown targets and threats (a mix of moving/static, evading/non-evading behaviours).

   We developed a method and a prototype able to efficiently solve the surveillance task problem considering all the needed characteristics described previously. The method was intended to:

   - Solve the surveillance problem using Reinforcement Learning (RL) techniques
     - Each UAV found a pattern automatically to solve the problem
   - Be distributed
   - Enable coordination between UAVs
   - Solve the problem in a real world context,
     - within a spatial environment
     - within a dynamic and uncertain environment
     - in a non-deterministic fashion

   This exploratory project gives a glimpse into what could be possible with this kind of approach. By combining reinforcement learning with a behaviour engine, automatic generation of agent's behaviours could easily be implemented. This work is a first step which could lead to automatic Courses of Action (COA) generation.

8. Bélanger, M., Berger, J., Perron, J., Hogan, J., Moulin, B., Exploitation of User's Preferences in Reinforcement Learning Decision Support Systems, 4th multidisciplinary workshop on Advances in Preference Handling (M-PREF 2008). Twenty-Third AAAI Conference on Artificial Intelligence (AAAI-08). Chicago, 2008. [10]

   A system called COLMAS (COordination Learning in Multi-Agent System) has been developed to investigate how the integration of realistic geosimulation and reinforcement learning might support a decision-maker in the context of cooperative patrolling. COLMAS is a model-driven automated decision support system combining geosimulation and reinforcement learning to compute near optimal solutions. Building upon this hybrid approach, this paper proposes an extended framework to constructively incorporate user preferences providing mixed-initiative generation of further trusted and validated solutions. The proposed approach integrates the user's preferences in COLMAS by automatically extracting user's preferred solution.

9. Perron, J., Hogan, J., Moulin, B., Berger, J.,Bélanger, M., A Hybrid Approach based on Multi-Agent Geosimulation and Reinforcement Learning to Solve a UAV Patrolling Problem. Unclassified, Winter Simulation Conference 2008, Miami, Florida, December 7-10, 2008. [11]

    In this paper we address a dynamic distributed patrolling problem where a team of autonomous UAVs patrolling moving targets over a large area must coordinate. We propose a hybrid approach combining multi-agent geosimulation and reinforcement learning enabling a group of agents to find near optimal solutions in realistic geo-referenced virtual environments. We present the COLMAS System which implements the proposed approach and show how a set of UAVs can automatically find patrolling patterns in a dynamic environment characterized by unknown obstacles and moving targets. We also comment the value of the approach based on limited computational results.

2.3 Dynamic vehicle routing

While in a dynamic uncertain environment, different combinations of sub-tasks can be required for a group of airborne sensors to conduct a real-time surveillance and reconnaissance mission. This section presents the work that was done to investigate hybrid genetic algorithms to solve dynamic vehicle routing problems.

10. Berger, J., Barkaoui, A., Boukhtouta, A., A Hybrid Genetic Approach for Airborne Sensor Vehicle Routing in Real-Time Reconnaissance Missions, Proceedings of Cognitive Systems with Interactive Sensors (COGIS), March 2006, Paris, France. [12]

    Past initiatives to address surveillance and reconnaissance mission planning mainly focused on low level control aspects such as real-time path planning and collision avoidance algorithms in limited environment. However, few efforts have been spent on high-level real-time task allocation. It is believed that automated decision capabilities supporting real-time resource allocation for sensor control and interactions might significantly reduce user workload, focusing attention on alternate tasks and objectives while delegating hard computational tasks to artificial agents. In this paper, we propose a new hybrid genetic algorithm to solve the dynamic vehicle routing problem with time windows, in which a group of airborne sensors are engaged in a reconnaissance mission evolving in a dynamic uncertain environment involving known and unknown targets/threats. In that context, visiting a target may consist in carrying out a collection of subtasks such as search, detect, recognize and confirm suspected targets, discover and confirm new ones. The approach consists in concurrently evolving two populations of solutions to minimize total traveled distance and temporal constraint violation using genetic operators combining variations of key concepts inspired from routing techniques and search strategies. A least commitment principle in servicing scheduled customers is also exploited to potentially improve solution quality.

2.4 Visibility –based terrain analysis for route planning

It is very important to understand the impact that the terrain has on the execution of an operation. The different terrain characteristics can be used to determine the visibility that resources will have when following different routes, as well as the range that weapons may have. This section presents the work that was done on a mathematical formalism and a verification methodology developed for visibility-based terrain analysis and route planning.

11. ESRI Canada, Evaluation of ESRI COTS Technology for Joint Combat Search and Rescue Research and Development Projects, CR 2006-584, March 2006. [13]

    The overall objective of the project is to provide DRDC with a proof of concept environment demonstrating a set of ESRI's Geographical Information System (GIS) Commercial Off The Shelf (COTS) products using scenario data provided by DRDC as it relates to a well defined subset of Combat Search and Rescue (CSAR) activities. Specifically, both the visualization of DRDC scenario data within a GIS environment and a demonstration of spatial analysis are included as part of the proof of concept. We have also included effort to explore the use of GIS tools in conjunction with DRDC CSAR data as well as the potential integration of existing algorithms and tools that have been created by DRDC with the GIS in subsequent phases of the project.

    This COTS evaluation was divided into three main sections as follows:

    1. Phase I – Data Integration: DRDC provided ESRI Canada with the necessary datasets to complete the software evaluation. Some pre-processing of this data was required to ensure compatibility.

    2. Phase II – Display Static and Moving Events from Synchronization Matrix: One dataset provided by DRDC was a table of temporal events for a CSAR scenario. ESRI Canada was required to convert this table into a GIS compatible format.

3. Phase III – Functionality Analysis

With three functional scenarios identified, Helicopter Landing Sites, Visibility Analysis and Temporal Display, evaluate ESRI ArcView as it relates to CSAR operations.

12. Maupin, P. and Jousselme, A.-L. Visibility-based terrain analysis and reasoning for combat search and rescue operations.

- In Worldwide Personnel Recovery Conference, NDIA, 2007. [14]
- In ESRI Canada Defence and Intelligence User Conference, Ottawa, ON, 31 May 2007. [15]

The aim of this paper is to present recent research on advanced concepts for Combat Search and Rescue (CSAR) operations made at DRDC-Valcartier. The work presented is based on the North Atlantis scenario GIS dataset, depicting a conflict taking place over an imaginary continent. The dataset is composed of topographic, hydrographic, transportation, and other typical land cover layers. The authors will depict a vignette tailored for the development of CSAR applications.

In this vignette, a CSAR operation is triggered on the second day following the commencement of the Alliance joint operations to secure Blueland territory and expel any Coalition invasion forces. A UK Royal Air Force Tornado was shot down over the Celtic Straits by a surface-to-air missile. The Tornado aircraft's wingman reported that both aircrew had ejected safely and downed crew had reported no injuries. In the process of extraction of the downed Tornado crew, the Sea King crashed. Two members of the Sea King crew sustained non-life-threatening injuries that have limited their mobility on foot. The Alliance will thus conduct a CSAR mission that will be part of Air Component Commander Campaign plan.

The authors will present the mathematical formalism and methodology proposed for visibility-based terrain analysis and reasoning for combat search and rescue operations. Applications presented will include landing site determination, shortest path to crash site as well as Ingress and Egress path determination.

3 A framework to support situation analysis

Situation analysis is the process of examining of a situation, its elements, and how those elements relate one another to provide and maintain a state of situation awareness for the decision maker. An important and difficult task of the situation analysis process is the characterization of uncertainty. A formalization approach of both knowledge and uncertainty has been investigated and used to define a framework to represent, combine, manage, reduce, increase and update knowledge, information and uncertainty. This framework is based on three main research themes relevant for high-level information fusion:

- Multiagent systems theories so that the distributed aspect can be adequately formalized;
- Decision theory in order to explicitly account for the actions and their impact on the environment; and
- Generalized Information Theory (GIT) for the representation of knowledge and uncertainty, including not only the traditional quantitative approaches but also their logical and sometimes qualitative counterparts.

The following are the publications produced during this project to describe the findings related to the modelization of the elements of knowledge of a situation and a framework intended to support situation analysis.

13. Maupin, P. Jousselme, A.-L., Vagueness in distributed systems: Review of recent formal models, in Proceedings of the XIIIth Congress of International Association for Fuzzy-Set Management and Economy, Hammamet, Tunisia, November 2006. [16]

> This paper proposes a review of recent formal models tackling the problem of representing vague concepts as well as reasoning about vagueness. A typology of the different kinds of vagueness is proposed and the authors draw correspondences to existing mathematical frameworks. The paper will particularly concentrate on vagueness related to distributed systems, seen as general formal models for systems made of interacting parts such as social networks, computer or economical networks composed of relatively autonomous agents. From a formal point of view, vagueness produces borderline cases, that can be represented in different manners: using a symbolic value for indetermination; using degrees corresponding to ill-defined set membership or truth values; defining granulations for the representation of indiscernible objects; and defining a richer universe of discourse to refine vague terms. The work presented in this paper, besides illustrating the different formal representation schemes for vagueness, explores the composition of mathematical functions as more general devices for the representation of vagueness. The authors consider in this paper the existence of three different kinds of vagueness: (1) Ontological vagueness, which is about the physical nature of objects, (2) Linguistic vagueness, due to the limitations of natural language and (3) Epistemic vagueness, caused by

the limitations of sensorial apparatus, lack of knowledge or computational limitations. Epistemic vagueness can diminish if more information is brought into the situation. Indeed because different kinds of vagueness can coexist in a single situation, a constructivist point of view is adopted as well as a general framework for representing vagueness. This said, how do we represent vague concepts and reason about vagueness in distributed systems? Furthermore, how do we cope with the different kinds of vagueness in distributed systems? The paper's main contribution is to sketch answers to these questions.

14. Jousselme, A.-L., and Maupin, P. Analyse de situation dans le cadre d'une coalition – Présentation d'un cadre formel. Technical Report DRDC Valcartier TR2007-003, DRDC Valcartier, March 2007. [17]

The general problem addressed in this work is the formalization of the analysis of a coalition formation. We proposed a formal model of coalition analysis, relying on the capacity of a coalition to thus achieve a mission. The realization of a mission implies on the one hand a planning task through the definition of a sequence of joint actions to be performed, and on the other hand the situation analysis that the coalition faces. These two tasks are in general regarded as distinct and the mathematical tools to treat them, different. The originality of the approach suggests tackling the problem of analysis of coalition rests on a general language used at the same time for the problems of planning and analysis of situation. Thanks to this approach, the process of planning can be founded on the effects (post-conditions) while accounting for the mental states of the agents, required as pre-conditions to actions. The generality of the formal language proposed makes it possible to bind the concepts of capacity and situation awareness, often considered and defined separately mainly because of the limitations of the tools used.

The specific problem approached in this report is that of formalization of the process of situation analysis. Formal definitions of situation, situational awareness, situation analysis are given. The modeling and the evolution of beliefs and knowledge as well as the associated uncertainty are defined in the network of agents which form a coalition. Thus are approached the concepts of group epistemic states, of conflict management, aggregation of information, of belief revision or update.

15. Bossé, É., Jousselme, A.-L., and Maupin, P. Situation Analysis for Decision Support: A Formal Approach. In Proceedings of 10th International Conference on Information Fusion (FUSION'2007), Québec, July 2007. [18]

Situation Awareness, a state in the mind of a human, is essential to conduct decision-making activities. It concerns the perception of the elements in the environment, the comprehension of their meaning, and the projection of their status in the near future [1]. Situation Analysis is defined as a process, the examination of a situation, its elements, and their relations, to provide and maintain a product, i. e., a state of situation awareness for the decision maker and information fusion is a key enabler to achieve that state.

Defence Research and Development Canada at Valcartier is pursuing the exploration of Situation Analysis concepts and the prototyping of computer-based decision support systems to maintain the state of situational awareness for the decision maker. The integration of the human element at the beginning of the analysis process is an important facet of our approach. This has been discussed in [2] where the objective was to ensure a cognitive fit to the decision-maker.

The situation analysis process has to deal with both knowledge and uncertainty and a formalization is necessary, defining a framework [3] in which knowledge, information and uncertainty can be represented, combined, managed, reduced, increased, updated. Characterizing and interpreting uncertainty are probably the most important and difficult tasks for the situation analysis process. From this characterization of uncertainty is derived the choice of the most adequate supporting concepts to the user. Up to recently, the data fusion process had often been portrayed as a purely passive, open loop treatment that simply transforms the pieces of information it receives.

Three main research themes should be considered for highlevel information fusion: Multiagent systems theories so that the distributed aspect can be adequately formalized, decision theory in order to explicitly account for the actions and their impact on the environment, and Generalized Information Theory (GIT) for the representation of knowledge and uncertainty.

This last theme is considered to include not only the traditional quantitative approaches but also their logical and sometimes qualitative counterparts. The highly formal approach proposed herein for the design of situation analysis and decision support systems seems unavoidable if one is interested in the reproducibility of results, in how much time and memory are needed to solve a problem, and most of all in a language to represent and reason about dynamic situations.

16. Maupin, P. and Jousselme, A.-L. Interpreted systems for situation analysis. In Proceedings of the 10th International Conference on Information Fusion, Quebec, Canada, 9-12 July 2007. [19]

This paper details and deepens a previous work where the Interpreted Systems semantics was proposed as a general framework for situation analysis. This framework is particularly efficient for representing and reasoning about knowledge and uncertainty when performing situation analysis tasks. Our approach to situation analysis is to base our analysis on the production of state transition systems consisting of the set of all temporal trajectories possibly obtained upon the execution of a given set of agents' protocols. Thus seen, the situation analysis task involves the definition of more or less subtle reasoning about graph structures. A formal situation analysis model is defined as an interpreted algorithmic belief change system. In such a model, the notions of situation, situation awareness and situation analysis are provided. The analysis of the situation is done through the verification of implicit notions of knowledge with temporal properties. Implicit knowledge is distinguished from explicit knowledge and situation awareness is defined in terms of the computing power of resource-bounded agents. A general plausibility measure allows us to model belief while making the link with quantitative representations of uncertainty such as probabilities, belief functions and possibilities. The proposed modeling of the situation analysis process, while compatible with the traditional implicit representation of knowledge found in modal logic, allows us to link the decision processes of the agents and their awareness of the situation with the observations they make about the environment.

17. Jousselme, A.-L., Maupin, P., Garion, C., Cholvy, L., Saurel, C. Situation awareness and ability in coalitions. In Proceedings of 10th International Conference on Information Fusion (FUSION'2007), Québec, July 2007. [20]

This paper proposes a discussion on the formal links between Situation Calculus and the semantics of interpreted systems as far as they relate to Higher-Level Information Fusion tasks. Among these tasks Situation Analysis requires the capacity to reason about the decision processes of coalitions. Indeed in higher levels of information fusion, one not only needs to know that a certain proposition is true (or that it has a certain numerical measure attached), but one also needs to model the circumstances under which this validity holds as well as agents' properties and constraints. In a previous paper the authors have proposed to use Interpreted System semantics as a potential candidate for the unification of all levels of information fusion. In the present work we show how the proposed framework allows binding reasoning about courses of action and Situation Awareness.

We propose in this paper (1) a model of coalition, (2) a model of ability in Situation Calculus language and (3) a model of situation awareness in Interpreted Systems Semantics. Combining the advantages of both Situation Calculus and the Interpreted Systems semantics, we show how Situation Calculus can be framed into Interpreted Systems semantics. Using the example of RAP compilation in a coalition context, we illustrate how ability and situation awareness interact and what benefit is gained. Finally, we conclude this study with a discussion of possible future works.

18. Mihai Cristian Florea, Anne-Laure Jousselme, Dominic Grenier, and Éloi Bossé. Approximation techniques for the transformation of fuzzy sets into random sets. Fuzzy sets and systems, 159:270–288, 2008. [21]

> With the recent rise of numerous theories for dealing with uncertain pieces of information, the problem of connection between different frames has become an issue. In particular, questions such as how to combine fuzzy sets with belief functions or probability measures often emerge. The alternative is either to define transformations between theories, or to use a general or unified framework in which all these theories can be framed. Random set theory has been proposed as a unified framework in which at least probability theory, evidence theory, possibility theory and fuzzy set theory can be represented. Whereas the transformations of belief functions or probability distributions into random sets are trivial, the transformations of fuzzy sets or possibility distributions into random sets lead to some issues. This paper is concerned with the transformation of fuzzy membership functions into random sets.
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> In practice, this transformation involves the creation of a large number of focal elements (subsets with non-null probability) based on the a-cuts of the fuzzy membership functions. In order to keep a computationally tractable fusion process, the large number of focal elements needs to be reduced by approximation techniques. In this paper, we propose three approximation techniques and compare them to classical approximations techniques used in evidence theory. The quality of the approximations is quantified using a distance between two random sets.
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19. Jousselme, A.-L. and Maupin, P. Analyse de situation dans North Atlantis - Application à la recherche et sauvetage au combat. Technical Report DRDC Valcartier TR200x-xxx, DRDC Valcartier, To be submitted. [22]

> Within the framework of the AS23 (Specific Arrangement 23 on the subject of collaborative decision making in a coalition context), we jointly proposed a formal model of coalition analysis, relying on the capacity of a coalition to conclude a mission. The realization of a mission implies on one hand a planning task through the definition of a sequence of joint actions to be performed, and on the other hand the situation analysis which the coalition faces. These two tasks are in general regarded as distinct and the mathematical tools to treat them, different. The originality of the approach suggests tackling the problem of analysis of coalition rests on a general language used at the same time for the problems of planning and analysis of situation. Thanks to this approach, the process of planning

can be founded on the effects (post-conditions) while accounting for the mental states of the agents, required as pre-conditions to actions. The generality of the formal language proposed makes it possible to bind the concepts of capacity and situation awareness, often considered and defined separately mainly because of the limitations of the tools used.

This report is the practical counterpart of the theoretical concepts defined in [17] which are applied to a CSAR mission in the North Atlantis scenario. Some communication graphs are detailed corresponding to (1) a CSAR mission in a coalition context, (2) the construction of the Recognized Air Picture, (3) operational communication of the assets. A terrain analysis combined with visibility properties is used to extract motion graphs that serve as a basis for agents' perception and mission planning. The problem of personal recovery is modelised as a pursuit-evasion problem, and the epistemic states of the agents are evaluated along different possible paths on the terrain. A module called PEGGI (Pursuit-Evasion in Graphs Generator Interface) is built based on an epistemic model checking technique to analyse the agents' joint strategy (protocol).

4 Approaches supporting situation awareness about planned operations

The RAP provides a means of monitoring the situation and developing an understanding of what is going on in the area of operations. The RAP also constitutes an important tool for developing Air Force plans and monitoring existing AF plans. Accordingly, the RAP needs to be able to support, in an efficient way, the management of plans. This section presents the work that has been done to support a common understanding of existing plans.

4.1 Plan representation

Air Force plans tend to be complex, involving many tasks, objectives and constraints. In order to develop decision support software for dynamic plan management, plans must be *represented* in a precise manner suitable for automated analysis. The management of existing plans (simple and complex, concurrent and sequential), the projection of plans in time, the evaluation/analysis of plans, as well as the real-time monitoring of plan evolution (considering expectations and assumptions identified during planning) are all aspects to consider when developing an understanding of current and future activities. To do so, the RAP should provide to decision-makers with all information related to a plan or a set of plans in an intuitive manner that facilitates plan understanding, analysis and monitoring in real-life operations. Plan visualization tools can also aid a commander in gaining a deep understanding of plan structure and plan status. This work was documented in the following papers.

20. Hunter, A., Happe, J., Dutkiewicz, M., Dynamic Plan Management in the Context of a Recognized Air Picture, Unclassified, CR 2007-446, November 2007. [23]

    This document surveys existing literature on dynamic plan management and describes the development of a prototype Air Force plan management system. The literature survey presents short summaries of a wide range of research papers, as well as a synthesis and analysis of existing approaches. The detailed comparison of existing approaches is used to formulate a specific methodology for the development of software for plan representation, plan forecasting/projection, plan analysis/evaluation and plan monitoring. The proposed methodology involves the development of a precise ontology of plan elements for plan representation. This representation removes ambiguity in the description of plans, facilitates automated analysis of plans, and also permits several different approaches to plan visualization. The implemented prototype software defines an ontology that provides a suitable internal representation of plans, along with basic plan validation capabilities. It also provides a map-based graphical user interface to visualize plans. The use of the software is demonstrated in the context of a combat search and rescue vignette. The findings conclude that the prototype demonstrates the overall utility of the approach, although further development is required to provide more detailed analysis, as well as additional visualization methods.

21. Happe, J., Techniques for Dynamic Multi-Plan Management, Unclassified, CR 2008-427, November 2008. [24]

    This report addresses the Canadian Air Force's need for an intuitive distributed, real-time multi-plan management system. The system must be capable of handling several plans in parallel, analyzing dependencies and possible conflicts (e.g. because of resource use) between plans. It must adequately cater to commanders, operators and users responsible for operations in different locations and at different levels of abstraction. It must respond to the highly dynamic and uncertain situation in the operational theatre and allow plan adaptations and repairs. On the other hand, it should not require military personnel to become knowledge experts, but instead it should display plans and plan elements in familiar, easy to absorb graphical and text-based representations. The amount of information should be tailored to the respective operator's need and devoid of unnecessary details, unless the operator specifically drills down for these details.

    The baseline for this project is the Recognized Air Picture Dynamic Plan Management (RAP/DPM) project, which offers an ontology-based data model suitable for the representation of multiple plans, albeit with some modifications. However, the plan and action data structures are too simplistic for modelling different levels of abstraction, and the visualization concepts do not cover all plan elements. Furthermore, it is desirable to furnish a formal concept for validating the correctness and executability of plans and attainment of the mission goals. The RAP/DPM project contributes a notion of effects and goals, which however is not rigid enough.

    This project borrows largely from the theory of Hierarchical Task Networks (HTN), a branch of AI planning. It supports the concept of hierarchical plan decomposition and instantiation of plan templates according to the given situation, locations, and resource assignments. The pure HTN approach falls short of military needs, though, as it has no notion of goals, nor of temporal concepts such as time points and durations. It also does not provide for plans and actions executing in parallel. Our main accomplishment is an adaptation of HTN to the existing RAP/DPM data model, incorporating ideas from Hierarchical Goal analysis and Effects-based Reasoning to represent and reason with goals and effects, as well as ideas from Scheduling Theory for reasoning with time.

    This document provides a rigorous description of all data elements related to plans, as well as the links and dependencies between them. To provide a specific and implementable representation UML is chosen as the modelling language. Furthermore, the document suggests possible approaches and algorithms for validating plans, as well as for user interaction with the plan execution.

The document also presents a high-level functional specification for a multi-plan management system, using UML use cases and component diagrams. Integral to this description are visualization concepts for an intuitive user interface. Among the features shown are a plan and goal hierarchy representing the user's scope of responsibility and allowing drill-down into lower-level goals and plans, a map view representing the spatial aspects of plans and/or goals, a schedule view representing the temporal allocation of plans and executing resources, a browser view allowing cross-hierarchy navigation and tracing of plan failures to the elements that caused them, and user dialogues to facilitate plan adaptations and changes. A proof-of-concept implementation of these features is available.

The proposed system is sufficiently generic and flexible to allow modelling plans outside the Air Force domain. The domain-specific knowledge really resides in the ontologies and task decomposition networks and can be replaced by, say, land-based or joint operational domains. The results of these reports and the benefits of the system are applicable, as long as there is a need for hierarchical (rather than linear procedural) planning and a mix of levels of abstraction for representing plans. The research findings also contribute beyond plan representation to the planning domain itself. In fact, even the currently proposed system allows adding and modifying plans; however, we would advise more research on suitable visual concepts to support planning and to automatically propose suitable plans for given planning problems.

4.2 Global coordinated plan

Coordination of actions and plans that must be achieved by multiple agents is one of the most difficult tasks in the multi-agent domain. In order to work together and achieve a common goal, agents need to coordinate their plans in a way that guarantees, if possible, the success of each individual agent plan. A temporal fusion mechanism has been proposed to allow a set of agents to fuse their plans to generate a global coordinated plan. This representation is useful for planning military operations taking place in dynamic environments where actions must be located in time with respect to the expected events. This work was documented in the following papers.

22. Allouche, M. K. and Boukhtouta, A. (2009), "Multi-Agent Coordination by Temporal Plan Fusion: Application to Combat Search and Rescue", International Journal on Information Fusion. [25]

The coordination of actions and plans that must be achieved by multiple agents is one of the most difficult tasks in the multi-agent domain. In order to work together and achieve a common goal, agents need to coordinate their plans in a way that guarantees, if possible, the success of each individual agent plan. In this work, we propose a temporal fusion mechanism that allows a set of agents to fuse their plans and generate a global coordinated plan. First, we define a temporal plan as a set of temporally constrained actions.

The fusion of several temporal plans is a temporal plan, which can be executed by several agents. The proposed framework is applied to a Combat Search and Rescue application.

5 Conclusion

This report has introduced the publications that were produced during the execution of the project 13dy "RAP Compilation and Exploitation for Dynamic Operations Management". Twenty-two publications were produced to document the investigations and their findings. Of these, 12 concern C2 concepts for gathering additional information in real time, 7 are about the description of a framework supporting situation analysis, and 3 are about concepts for integrating our own plans in the global understanding of the situation.

Through the execution of this project, we were able to conduct investigations on most of the aspects that identified as requiring R&D to support RAP compilation and exploitation. These investigations covered aspects the following:

- Identification of the types of information that could improve SA (RAP enablers);
- Information gathering strategies required to compile an air picture;
- Identification of dynamic resource planning models and algorithms for near real-time and real-time information collection (collection management enablers);
- Dynamic change detection and relationship discovery techniques;
- Situation and event recognition system requirements;
- Situation forecasting and prediction techniques;
- Intelligent adaptive interface;
- Visualization techniques (e.g., to represent dynamic relationships, etc.);
- User interface guidelines for RAP display;
- Approaches/strategies/techniques for dynamic air operations planning and management;
- Approaches/strategies/techniques to provide real-time airspace deconfliction capabilities.
- Approaches/strategies/techniques for real-time mission execution and feed-back;
- Plan representation;
- Plan simulation;
- Plan forecasting approaches;
- What-if analysis approaches.

These investigations led to the identification of promising techniques and approaches to support RAP compilation and exploitation. However, it is important to mention that, due to time and resource constraints, none of the aspects investigated have reached the level of maturity required to support the development of an effective situation awareness required for a military operational context. Furthermore, further experimentation is needed to determine the level of support that a RAP display can provide for a common and shared mental model of the air battlefield.

Considering that the RAP is only part of a common operating picture, it is recommended to pursue the investigation of the concepts identified in this project for the other military environments. The integration of the findings thus identified with the results from this project could lead to the development of the global situation awareness required for the conduct of military operations.

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List of symbols/abbreviations/acronyms/initialisms

DND	Department of National Defence
C4ISR	Command, Control, Communication, Computer, Intelligence, Surveillance and Reconnaissance
COLMAS	COordination Learning in Multi-Agent System
COTS	Commercial Off The Shelf
CSAR	Combat Search And Rescue
DRDC	Defence Research & Development Canada
DRDKIM	Director Research and Development Knowledge and Information Management
GIS	Geographical Information System
GIT	Generalized Information Theory
ISR	Intelligence, Surveillance, Reconnaissance
M-PREF	Multidisciplinary Workshop on Advances in Preference Handling
ML	Machine Learning
R&D	Research & Development
RL	Reinforcement Learning
RAP	Recognized Air Picture
SA	Situation Awareness
UAV	Unmanned Aerial Vehicle

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This close-out report of the project 13dy "RAP Compilation and Exploitation for Dynamic Operations Management" identifies the documents that were published to describe the concepts investigated during the execution of this project. These concepts include:

- Real-time gathering of missing information about the area of operations;
- A framework supporting the situation analysis; and
- Integration of plans in the global understanding of the situation.

Ce rapport synthèse du projet 13dy « Compilation et exploitation d'une image opérationnelle aérienne pour la gestion dynamique des opérations » identifie les documents qui ont été publiés pour décrire les concepts étudiés dans ce projet. Ces concepts incluent:

- La saisie en temps réel d'informations manquantes sur la zone d'opération;
- Un cadre de travail pour l'analyse de situation; et
- L'intégration des plans dans la compréhension globale de la situation.

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RAP; Recognized Air Picture; Situation Analysis; Cooperative Search-Path; Dynamic Distributed Patrolling; Dynamic Vehicle Routing; Visibility-based Terrain Analysis for Route Planning; Plan Representation; Global Coordinated Plan