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KARMA: Knowledge-based Adaptive Resource Management Agent

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Technical Report

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Abstract

A knowledge-based adaptive resource management agent (KARMA) to support dynamic planning and execution monitoring in a time-constrained uncertain military environment is presented. Based upon a parallel blackboard architecture, KARMA relies on the concept of adaptive planning which interleaves plan construction and plan execution allowing accurate planning when time is available and coarse fast planning under time pressure, trading-off solution quality and run-time computation. The adaptive planning concept shown by the KARMA prototype has been applied to an Army Aviation Fleet context, namely to a tactical squadron domain level to support mission planning (air vehicle routing and crew scheduling), and clearly shows applicability to alternate military domains and components as well.

Résumé

Un agent de gestion des ressources adaptatives à base de connaissances (KARMA) supportant la planification dynamique et le monitoring d'exécution dans un environnement militaire temporellement contraint et incertain est présenté. Basé sur une architecture parallèle de type tableau noir, KARMA repose sur le concept de planification adaptative qui combine la construction et l'exécution de plans, permettant une planification précise ou grossière/approximative en fonction du temps disponible, transigeant qualité de solution et temps de calcul. Le concept de planification adaptative illustré par KARMA a été appliqué au contexte de flotte d'aviation de l'armée (Army Aviation Fleet), notamment dans le cas d'un escadron tactique afin de supporter la planification de missions, et montre une applicabilité évidente dans d'autres domaines et services militaires.

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Executive summary

Automated and flexible capabilities to support tactical mission planning present a major challenge for the Canadian Air Forces. This is motivated by mission demand, nature and diversity, resource heterogeneity, multiplicity and availability; environment predictability, dynamic evolution; reaction time, and cost-effective resource utilization and coordination at different levels. Reactive planning systems operating in a dynamic uncertain environment can usually work in real-time but do not guarantee efficient solutions for large problems, whereas deliberative systems are able to compute optimal solutions, but conditionally on the perfect knowledge of the world and the use of unbounded computational resources. However, a real artificial/natural agent evolving in a dynamic world must deal with uncertainty, incomplete information domain, finite and limited computational power.

This document presents a knowledge-based adaptive resource management agent (KARMA) to support dynamic planning and execution monitoring control in a time-constrained uncertain military environment. Based upon a parallel blackboard architecture, KARMA relies on the concept of adaptive planning which interleaves plan construction and plan execution, allowing accurate planning when time is available and coarse fast planning under time pressure, trading-off solution quality and run-time computation. The adaptive planning concept shown by the KARMA prototype has been applied to an Army Aviation Fleet context, namely to a Tactical Helicopter Squadron problem domain to support mission planning (air vehicle routing and crew scheduling).

The KARMA prototype has been successfully demonstrated in international military JWID (Joint Warrior Interoperability Demonstration) 2001 and 2002 exercises. Perfectly compatible with the objectives of the Air Force Command and Control Information System (AFCCIS) project to support resource planning, the KARMA prototype can be easily seen as a separate component or module to be integrated into an Air Force command and control information system. Discussions on a technology transfer through an evolutionary transition process to the AFCCIS project have been initiated and are still ongoing. The proposed KARMA technology concept demonstrated within the Army Aviation Fleet context (tactical level) clearly shows applicability to alternate military domains and components as well, including Fighter Fleet, Air Transport Fleet and Maritime Air Fleet activities to name a few. This work is quite relevant to recent international TTCP activities, namely, C3I AG-1 (Dynamic Planning and Execution) and JSA AG-11 (Distributed Intelligent Systems).

KARMA represents a significant contribution to tackle key resource management problems faced by the Canadian Air Force to support dynamic planning in a time-constrained uncertain environment. This

initiative improved DRDC Valcartier's position and capacity in its role to properly advise the CF during the eventual evaluation and acquisition of decision support system components.

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Sommaire

Le support à la planification tactique automatisé présente un défi majeur pour les Forces aériennes canadiennes. Ceci est motivé par la demande en missions, leur nature et diversité, l'hétérogénéité des ressources, leur multiplicité et disponibilité, la prévisibilité de l'environnement, son évolution dynamique, le temps de réaction, et l'allocation et la coordination efficaces de ressources à différents niveaux. Les systèmes de planification réactive évoluant dans un environnement dynamique fonctionnent en temps réel mais ne peuvent garantir de solutions efficaces pour des problèmes de grande taille, alors que les systèmes délibératifs en mesure d'obtenir des solutions optimales exigent une connaissance parfaite du monde et une puissance de calcul illimitée. Cependant, un véritable agent doit composer avec l'incertitude, une information incomplète du domaine, une puissance de calcul limitée.

Ce document présente KARMA, un agent de gestion des ressources adaptatives à base de connaissances supportant la planification dynamique et le monitoring d'exécution dans un environnement militaire temporellement restreint et incertain. Basé sur une architecture de type tableau noir parallèle, KARMA repose sur le concept de planification adaptative qui combine la construction et l'exécution de plans permettant une planification précise ou grossière/approximative en fonction du temps disponible, arbitrant qualité de solution et temps de calcul. Le concept de planification adaptative illustré par KARMA a été appliqué au contexte d'une flotte d'aviation de l'armée (Army Aviation Fleet), notamment dans le cas d'un escadron d'hélicoptères tactique afin de supporter la planification de missions (tournées de véhicules et d'équipages).

Le prototype KARMA a été expérimenté avec succès lors des exercices militaires internationaux JWID (Joint Warrior Interoperability Demonstration) 2001 et 2002. Tout à fait compatible avec les objectifs du projet Système d'information de commandement et contrôle des forces aériennes (AFCCIS) pour la planification des ressources, le prototype KARMA peut être facilement considéré comme une composante ou un module séparé pouvant être intégré à un système d'information de commandement et contrôle des forces aériennes. Des discussions sur un transfert technologique suivant un processus de transition évolutif au projet AFCCIS ont été engagées et se poursuivent. Le concept technologique proposé KARMA, démontré dans le contexte de flotte d'aviation de l'armée (niveau tactique) se révèle tout autant applicable à d'autres domaines militaires, tels que les flottes d'avions chasseurs, de transport aérien et les activités de la flotte aérienne maritime pour ne nommer que ceux-la. Ce travail est tout à fait pertinent aux récentes activités internationales TTCP, notamment C3I AG-1 (Planification dynamique et exécution) et JSA AG-11 (Systèmes intelligents répartis).

KARMA représente une contribution significative aux problèmes clés de la gestion des ressources auxquels doivent faire face les Forces aériennes canadiennes pour supporter la planification dynamique dans un environnement restreint dans le temps et incertain. Cette initiative a amélioré la position et la capacité de RDDC Valcartier dans son rôle de conseiller auprès des Forces canadiennes dans l'évaluation et l'acquisition éventuelle de composantes de systèmes d'aide à la décision.

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1. Introduction

Reactive planning systems operating in a dynamic military environment work in real-time but cannot guarantee efficient solutions for large problems, whereas deliberative systems are able to provide optimal solutions, but conditionally on a perfect knowledge of the world and the use of unbounded computational resources for large state space problems. However, a real artificial/natural agent evolving in a dynamic world must deal with uncertainty, incomplete information domain, a finite and limited computational power, imprecise sensing, and must regard planning time as another degree of freedom. Accordingly, a fair balance between reactive and deliberative planning must be achieved which will allow accurate but slow planning when time is available, and fast coarse planning when operating under time pressure.

In this document, a knowledge-based adaptive resource management agent to support dynamic planning and execution monitoring control in a time-constrained uncertain military environment is proposed. Based upon a parallel blackboard architecture, KARMA relies on the concept of adaptive planning which intertwines plan construction and plan execution allowing accurate planning when time is available and coarse fast planning when operating under time pressure, trading-off solution quality and run-time computation. The adaptive planning concept conveyed by KARMA is applied to an Army Aviation Fleet context, namely, the Tactical Helicopter Squadron 430 ETAH operating under 1-Wing, to support mission planning (air vehicle routing and crew scheduling). The KARMA application can be summarized as follows. Based on a limited mission model and specifications, a mission is decomposed in a task structure related to a predefined goal/sub-goal hierarchy (one-to-one correspondence). Tasks or subtasks such as planning and execution monitoring are achieved by specialized knowledge sources primarily activated and controlled by a mixed goal-directed and event-driven control unit. Knowledge sources are specifically designed to achieve cognitive tasks at different abstraction levels. For instance, an airlift mission does require various specialized planning knowledge sources from the selection of a suitable aircraft (utility tactical helicopter) to the assignment of a qualified crew (pilots, flight engineer) and plan monitoring, repair or revision (if required) tasks. Based on goal hierarchy, additional knowledge sources are also invoked and supervised by the controller to achieve situation and multi-level mission monitoring tasks and mission plan dispatching in due time. Event-driven control concurrently takes place to monitor and handle new events, closing the sense-plan-act loop. Besides, KARMA proposes some primitive form of mixed-initiative planning or capabilities to support human-computer interaction, a suitable property for any advisory decision support system component.

The report is outlined as follows. Chapter 2 introduces a simplified description of the targeted air vehicle scheduling/routing and crew scheduling problem to be addressed at Squadron 430. An overview of the proposed KARMA solution is then given in Chapter 3. The basic features of the baseline system architecture and application modeling characteristics are presented. Then, Chapter 4 reports demonstrations of the KARMA prototype in which the value of the proposed approach is briefly discussed. A discussion on the strengths of the underlying KARMA technology immediately follows in Chapter 5. Finally, we conclude with a short summary in Chapter 6.

This work was conducted at DRDC Valcartier between January 1998 and August 2003 within Work Unit 13dm11: *Adaptive Intelligent System* of project 3dm: *Mission Planning*.

2. Problem domain

Dynamic planning and execution monitoring problems are pervasive through the Canadian Air Force, especially at the operational and tactical mission level. Accordingly, the nature and scope of problems and solutions to be investigated may significantly impact the quality of the plan development and plan review stages of the Canadian Forces Operations Planning Process (CFOPP) [1]. In this report, specific attention will be devoted to a common mission planning class of problems faced by tactical units (Air Squadron) [2, 3] in a time-constrained environment or deployment situation, namely, vehicle (aircraft) scheduling/routing and crew (pilots and flight engineers) scheduling with time windows, subject to a variety of mission and resource constraints. Contrarily to a family of models based on the closed-world assumption and a finite time horizon, the current problem setting emphasizes continual (rolling time horizon) open-ended planning.

In this problem, mission planning is achieved by constructing plans to dispatch air defence resources (aircraft, personnel) in order to respond to a periodic and continuous flow of real-time mission requests (transport, assistance, training) as illustrated in Figure 1. The tactical unit (Tactical Helicopter Squadron 430 ETAH) through the local resource controller receives mission requests ("helquests") from various sources or clients (e.g. Land Force services and Air Command Operations Center, both through 1-Wing, 5 CMBG) and allocate resources (helicopters, pilots and flight engineers), generating mission plans. Mission requests are assumed to be heterogeneous and generated randomly. These missions are planned and concurrently combined to a suitable set or sequences of training missions determined by training policies over a finite horizon (weeks, months), to maintain aircraft and personnel readiness or qualifications. In practice, planning is tentatively made on a periodic basis (daily, monthly) despite a rolling horizon and a time-varying environment. Requests related to transport, assistance and training purposes may involve more or less sophisticated features of scheduling, routing, pick-up and delivery tasks or a complex mix of them. Targeted objectives in planning missions may involve single or multiple criteria, including serviceability and economic attributes (e.g. cost, resource consumption), makespan, overall or specific mission request coverage and/or rate (throughput) over a single or multiple episodes, etc. Problem instances could be generated or adapted to suit a particular context emerging from various situations such as air contingency, air defence (sovereignty of the territory) and

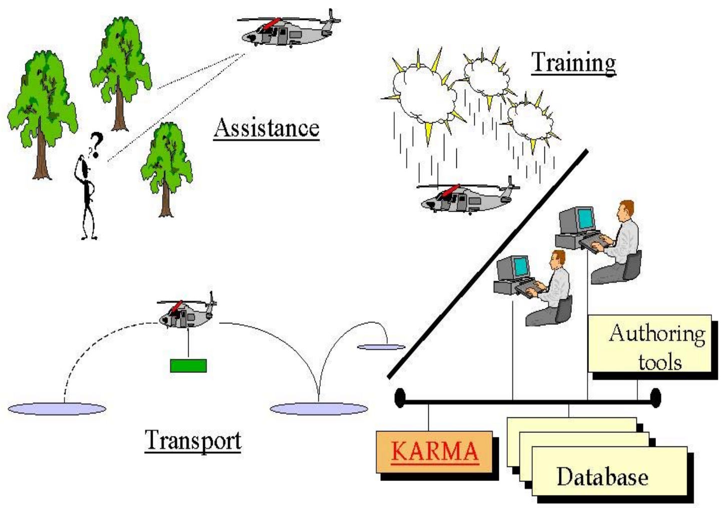

Figure 1 - Dynamic planning and execution control - Tactical mission planning

emergency management operations. In the current setting, vehicle (aircraft) scheduling/routing and crew (pilots, flight engineer) scheduling, will primarily be restricted to a single depot of vehicles. The multi-depot problem characterized by distributed resources subject to either centralized or distributed collaborative continual planning is partly addressed, as a more extensive and separate investigation to tackle this problem is delayed to a future stage.

The mission model being proposed is characterized by a set of attributes such as mission identifier, goal, type, priority, time window to initiate the mission, deadline, and a collection of tasks. Likewise, task definition includes similar elements, namely, task identifier, goal, type (transport, assistance and training), priority, resource requirements (vehicle: number, configuration; crew: composition, qualifications), locations (origin, destination), payload characteristics (freight, passengers, weight, volume), time window to start the task, duration (including debriefing) and deadline. Tasks correspond to basic mission building blocks. Accordingly, a mission can be broken down at various abstraction levels through a hierarchical task network structure until elementary (terminal) subtasks are specified. An elementary task (terminal node) refers to basic flight segments or "legs" associated to a vehicle (utility tactical and transport helicopter). For instance, an elementary task ("heltask") might consist in using a helicopter, two pilots and one flight engineer to transport cargo or personnel from an origin location (base or vehicle depot) to a destination, and then return to the base. In this model, full mission decomposition in elementary components is assumed to be a prior knowledge. In KARMA (prototype), knowledge related to mission breakdown specification is owned by the user. Tasks relate to each other by precedence or temporal constraints, and can be implicitly structured or ordered according to temporal constraints. A mission is accomplished when all its task components' goals have been successfully achieved. This event progressively takes place over the mission hierarchical task network structure through a backtracking mechanism, propagating goal satisfaction from children to parent tasks.

Mission planning and execution involves vehicles (helicopters) and crew personnel resources, both affiliated to a single depot. Vehicles are characterized by the following attributes: vehicle identifier, type, autonomy over different periods (per sortie and day), capacity (weight, volume with respect to freight), quantity, configuration and equipment, configuration set-up time, failure rate (mean time between failure) and sequence of periodic maintenance. A personnel member is described with the following attributes: a personnel identifier, type (pilot, flight engineer), qualifications, periodic flight, duty and rest requirements, periodic flight training requirements, availability and training record. A typical mission crew requires a pilot, co-pilot and a flight engineer.

General assumptions characterize the environment model of the problem under study. In this simplistic environment model, we postulate mission independence and no pre-emptive tasks, even though training missions or tasks can sometimes be performed simultaneously, sharing the same resources. For instance, transportation and training missions can be concurrently combined, using the same resources. Vehicles are assumed to travel at constant speed, based on a uniform rectilinear motion model, and travel time is considered purely distance-proportional. As for vehicle maintenance, the current model does not explicitly represent the four-level service normally required, from minor repairs to full inspection. It simply assumes a fixed lower bound on the number of serviceable aircraft, at any time. In other respect, several sources of uncertainty such as weather conditions, resource availability and/or failures, mission occurrence, types, duration, start and termination time, and human intervention or other phenomena do naturally characterize the problem domain. Usually represented by stochastic distribution models (under the closed-world assumption), the current environment setting assumes no particular or prior knowledge about the probabilistic nature of these observable events (open-world assumption). As a result, sequential decision has not been explicitly captured as part of the decision process used to handle uncertainty. An "open-loop feedback" approach has been preferred.

A mathematical model depicting the salient features of the problem stated above over a finite time horizon can be described through a basic vehicle scheduling problem model. Accordingly, a possible problem formulation can be described as follows:

Problem formulation

Notation: Let *N* be the set of mission (elementary task) and *K* the set of vehicles to be routed and scheduled. The graphs $G^k=(V^k, A^k)$ for each vehicle *k* involve a set of nodes V^k and a set of feasible arcs A^k. V^k is defined by $N \cup \{o(k), d(k)\}$ where *o(k)* and *d(k)* refer to origin-depot and destination-depot associated to vehicle *k*, $k \in K$. The set A^k includes all feasible (mission compatibility) arcs representing a subset of $V^k \mathrm{x} V^k$. Each arc *(i,j)* of A^k is characterized by a cost c_{ij}^{kr} and a travel time t_{ij}^{k} involving vehicle *k* over a given tour *r*. Travel time is assumed to include activity duration associated with mission *i*. A tour or similarly a route performed by vehicle *k* is characterized by a sequence of missions starting and terminating at the given vehicle depot location (*o(k)* = *d(k)*). The fleet is composed of *v* homogeneous vehicles, limiting concurrent tours to the same number. However, the same vehicle can be reused (multi-trip vehicle) to perform multiple tours $r \in R$, up to R_{max} routes. Each route *r* related to vehicle *k* carried out over time interval $[\mathrm{T}_s^{kr}, \mathrm{T}_{end}^{kr}]$ is subject to a maximum duration *D*. The problem formulation includes flow binary variables X_{ij}^{kr} equal to 1 if vehicle *k* over route *r* is assigned mission *j* after fulfilling mission *i*, and 0 otherwise, and, time variables T_i^{kr} referring to the start of mission *i* by vehicle *k* over route *r*. Mission *i* must be initiated over the time interval $[a_i, b_i]$. It is assumed that time variables can be instantiated over the discrete set of values TS.

$$Min \sum_{k \in K} \sum_{r \in R} \sum_{(i,j) \in A^k} c_{ij}^{kr} X_{ij}^{kr} \tag{1}$$

subject to:

Mission coverage:

$$\sum_{k\in K}\sum_{r\in R}\sum_{j\in N\cup\{d(k)\}} X_{ij}^{kr} = 1 \qquad \forall i \in N \qquad (2)$$

Flow:

$$\sum_{j\in N\cup\{d(k)\}} X_{o(k)j}^{kr} = 1 \qquad \forall k \in K,\ \forall r \in R \qquad (3)$$

$$\sum_{i\in N\cup\{o(k)\}} X_{ij}^{kr} - \sum_{i\in N\cup\{d(k)\}} X_{ji}^{kr} = 0 \qquad \forall k \in K,\ \forall r \in R,\ \forall j \in V^k \setminus \{o(k), d(k)\} \qquad (4)$$

$$\sum_{i\in N\cup\{o(k)\}} X_{id(k)}^{kr} = 1 \qquad \forall k \in K,\ \forall r \in R \qquad (5)$$

Schedule feasibility:

$$X_{ij}^{kr}(T_i^{kr} + t_{ij}^k - T_j^{kr}) \le 0 \qquad \forall k \in K,\ \forall r \in R,\ \forall (i,j) \in A^k \qquad (6)$$

$$a_i \le T_i^{kr} \le b_i \qquad \forall k \in K,\ \forall r \in R, \forall i \in V^k \qquad (7)$$

Tour (start and end time):

$$\mathrm{T_s^{kr}} = \max(j \in N)\{X_{o(k)j}^{kr}(T_j^{kr} - t_{o(k)j}^k)\} \quad \textit{tour r (vehicle k) lower bound} \qquad (8)$$

$$\mathrm{T}_{end}^{\mathrm{kr}} = \max(i \in N)\{X_{id(k)}^{kr}(T_i^{kr} + t_{id(k)}^k)\} \quad \textit{tour r (vehicle k) upper bound} \qquad (9)$$

Itinerary (maximum tour duration)

$$\mathrm{T}_{end}^{\mathrm{kr}} - \mathrm{T_s^{kr}} \le D \qquad \forall k \in K,\ \forall r \in R \qquad (10)$$

Maximum number of vehicles *v*:

$$\sum_{k\in K}\sum_{r\in R}\sum_{j\in N} X_{o(k)j}^{kr}\,\mathrm{S}(t - \mathrm{T_s^{kr}})\mathrm{S}(\mathrm{T}_{end}^{\mathrm{kr}} - t) \le v \quad \forall t \in TS \qquad (11)$$

Multi-trip vehicle: non-simultaneous vehicle tours

$$1 - \mathrm{S}(\mathrm{T}_{end}^{\mathrm{kr}} - \mathrm{T_s}^{kr'})\mathrm{S}(\mathrm{T}_{end}^{\mathrm{kr'}} - \mathrm{T_s^{kr}}) \succ 0 \qquad \forall k \in K,\ \forall r, r' \in R,\ r \ne r' \qquad (12)$$

Multi-trip vehicle: incremental route construction

$$\mathrm{S}\Big(\sum_{(i,j)\in NxN\setminus(o(k),d(k))} X_{ij}^{kr}\Big)\Big(1 - S\Big(\sum_{(i,j)\in NxN\setminus(o(k),d(k))} X_{ij}^{k,r-l}\Big)\Big) = 0 \quad \forall k \in K, r \succ 1,\ l = 1..r\text{-}1 \qquad (13)$$

$$\Big(1 - S\Big(\sum_{(i,j)\in NxN\setminus(o(k),d(k))} X_{ij}^{kr}\Big)\Big)S\Big(\sum_{(i,j)\in NxN\setminus(o(k),d(k))} X_{ij}^{k,r+l}\Big) = 0 \quad \forall k \in K,\ r \prec R_{\max},\ l = 1..R_{\max} - r$$

(14)

$$X_{ij}^{kr} \in \{0,1\} \qquad \forall k \in K,\ \forall r \in R,\ \forall (i,j) \in A^k \quad (15)$$

$$\mathrm{S}(x) = \begin{cases} 1 & if \quad x \succ 0 \\ 0 & otherwise \end{cases} \qquad \textit{(step function)} \quad (16)$$

The problem consists in minimizing the objective function (1) subject to various constraint sets. The objective or cost function may represent total distance, cumulative resource expenditure or any combinations of key problem attributes. The mission coverage constraint described by Equation (2) imposes all missions to be covered exactly once. The flow conservation constraints ensuring legal route construction (starting and terminating at the depots) are expressed by Equations (3-5). Constraint set given by Equations (6-7) involves traveling time (including mission execution time) required to initiate the execution of another mission and a time window over which a mission must start. Tour duration is bounded to a preset limit to reflect resource utilization time constraint as depicted through the itinerary constraint expressed by Equation (10) in which tour start and end times are given by Equations (8-9). The number of reusable vehicles to be concurrently used is translated into Equation (11) for fleet size. Constraint set associated with vehicle reusability (multi-trip vehicle or cycles) to carry out multiple missions over the same time horizon is described by Equations (12-14). Equation (12) simply ensures that mission execution and traveling periods involving the same vehicle do not overlap while Equations (13-14) illustrate incremental route construction. In that context, one may assume that $o(k) = d(k)$.

Crew could be incorporated into the problem model and handled concurrently with vehicles through extended (coupled) or separate (decoupled) decision variables. Additional constraints such as time intervals associated with resource (aircraft, crew) utilization (availability/non-availability) or time horizon have been deliberately omitted from the incomplete mathematical model to focus on essential elements and keep readability acceptable. However, it is assumed that these constraints are handled directly by the problem-solving method and the rolling horizon determined by the occurrence of new events (new mission, expected and effective mission start/completion time, resource status change, world state transition, etc.). Alternate static mathematical models capturing primitive simultaneous vehicle and crew scheduling problems involving basic limited features have also been recently proposed [4].

3. KARMA - Solution

The solution proposed to the dynamic mission planning problem introduced in the previous chapter relies on the knowledge-based adaptive resource management agent (KARMA) system. An adaptive intelligent system is explicitly designed to modify its behavior in response to a dynamic and uncertain environment in order to successfully reach its goals [5]. KARMA is a significant contribution toward the development of a real-time advisory decision support system capability for resource management.

3.1 System architecture

The KARMA architecture is part of a recent effort aimed at developing advanced technology concepts and tools for an adaptive intelligent system to assist the military community in the management of air defence resources related to air command and control activities [5]. The baseline architecture is depicted in Figure 2. It is inspired from the basic “blackboard” paradigm [6]. The underlying blackboard concept relies on the opportunistic interaction of multiple experts (knowledge sources) sharing and communicating information through a common blackboard (data storage). Specialists reflected through knowledge sources cooperatively contribute to the overall problem-solving process (solution of a common complex problem) by gradually solving a hierarchy of related subproblems. The information is shared through a common workspace or shared memory called blackboard. The timely interaction and execution of suitable sources of expertise is mediated by a special control unit.

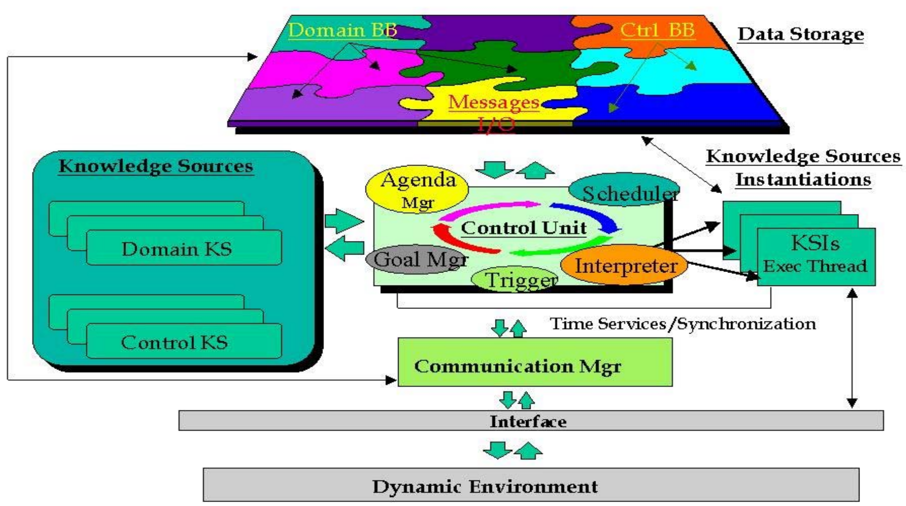

Figure 2 - Parallel blackboard architecture

The proposed approach consists in evolving the basic blackboard paradigm, addressing its intrinsic deficiencies and suitably adapting the problem-solving process to support real-time planning in time-varying and uncertain environment. The proposed parallel blackboard architecture allows for the concurrent execution of multiple knowledge sources (KSs), while enhancing the control unit by adding explicitly goal-directed control and a meta-level control mechanism to support resource-bounded reasoning. The meta-level control of reasoning is responsible for deliberation scheduling and run-time monitoring of anytime algorithms [7], and then explicitly introduces a mechanism to interleave dynamic plan construction and plan execution. The basic implementation of the parallel blackboard mainly involves four major components, namely the blackboard data storage, the knowledge sources, the control unit and the communication manager. It focuses upon a centralized control process which supervises the execution of multiple knowledge sources running concurrently and interacting through the blackboard data storage. Key technology involve knowledge-based blackboard system, resource-bounded reasoning techniques, evolutionary computation, agent communication language, concurrent problem-solving through multithreading, concurrency control, object-oriented design/technology, client-server and relational database. An overview of the basic concepts may be found in [8]. The reader can also refer to [5] for more technical details upon the baseline architecture.

In the Army Aviation context, tactical mission planning evolves in a closed-loop sense-plan-act environment. System information flow can be easily illustrated through a simple example. For instance, mission requests transiting from the external environment through a user interface layer (typically a database) to the communication manager are first deposited as messages on the blackboard data storage. The latter refers to a shared memory containing various information of the problem domain (past and current mission requests and plans, ongoing action plans, aircraft and personnel state variables, weather conditions, etc.). As a result, an incoming event is generated on the blackboard. This event is handled and processed by the control unit to determine potential knowledge sources (typically planning knowledge sources) to be instantiated. The control unit then selects the most relevant knowledge sources to be activated. Accordingly, execution of a selected knowledge source instance either generates new events bound to trigger lower level knowledge sources responsible for constructing a more detailed mission plan, or dispatches information (mission plans) to the database, closing the sense-plan-act loop. Unexpected events leading to plan revision or mission termination are handled in a similar way. In order to support human-computer interaction, a mixed-initiative solution has been proposed as well. In addition to accept, reject and alter plans proposed by the system, the human can also generate brand new plans independently. On-line planning can then be achieved through automated or mixed control.

3.2 Application

3.2.1 Overview:

An initialization procedure first sets up basic environment processes generating basic data structures including a goal structure (initial persistent goal), knowledge bases and knowledge sources. The procedure then executes a special knowledge source (InitKS) performing queries on the database to successfully initiate the tactical mission planning process.

The KARMA closed-loop solution (open-loop decision model with environment feedback) includes the contribution of various types of goal and data -driven knowledge sources (KSs) referring to multi-level planning, monitoring and dispatching (mission plan dissemination to the database) tasks. KS planners involve incremental planning and plan repair tasks. High-level KSs timely post a hierarchy of goals (Figure 3) to be achieved through the execution of low-level planning KSs responsible to generate action plans to satisfy subgoals. As a result, a sequence of new or updated action plans is successfully computed and eventually disseminated (KS dispatcher) to the database. Low-level KS monitors are then scheduled to validate action plans before (pre-conditions) and during execution. Accordingly, while ongoing high-level KS monitors continually focus attention on global world (domain) situation changes, low-level KSs separately monitor elementary task plan executions. KARMA monitoring tasks are facilitated using the tactical database interface to dynamically update desired information and set monitoring and control parameters. Should an unexpected event or new opportunity occur, the controller would be informed immediately. Consequently, as KS selection and scheduling is mediated by the control unit (goal-directed scheme) which determines suitable goal(s) to be pursued next, a plan repair or a new (re)planning knowledge source might be further activated. Environment feedback is handled by data-driven knowledge sources.

3.2.2 Knowledge sources

A single high-level persistent objective mainly drives KARMA knowledge source execution. This objective simply consists in successfully planning and achieving all submitted mission requests, as depicted by the root "AllMissionsAchieved" goal shown in Figure 3. Goal-directed and data-driven knowledge sources operating at different abstraction levels progressively expand goal hierarchy (Figure 3) producing indirect interactions between various types of knowledge sources. Key knowledge sources are described next.

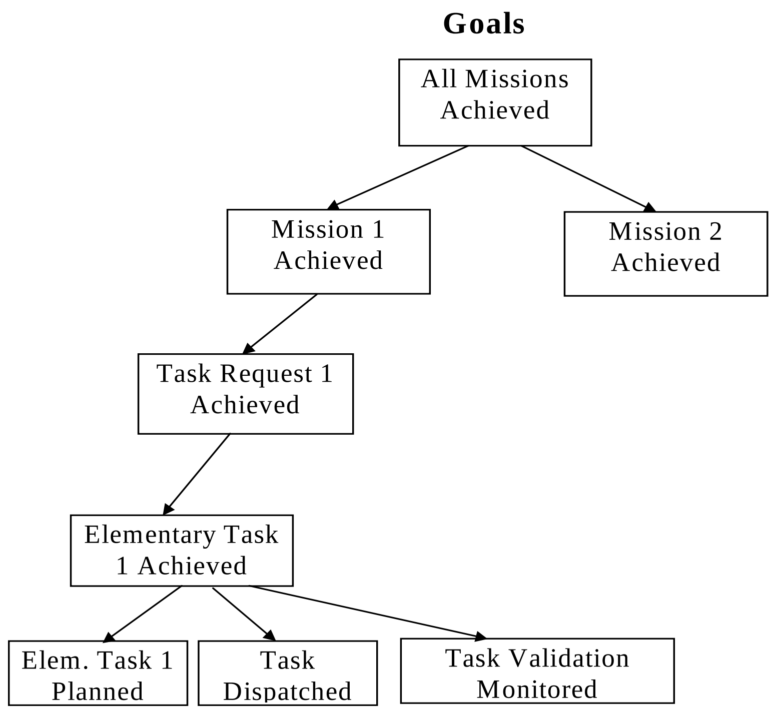

Figure 3 - Goal hierarchy

3.2.2.1 Planning:

Mission request planning is carried out sequentially on a “first arrival, first planned” basis. As planning occurs over a rolling time horizon involving dynamic constraints, problem formulation explicitly stated in Chapter 2 has been deliberately ignored. Many KSs contribute to achieve planning tasks. On a new mission request initially detected with the MissionMonitorKS KS, a "MissionAchieved" goal is first generated as pictured in Figure 3. Consequently, "TaskRequestAchieved" subgoals are then created through MissionTaskRequestMonitorKS instances matching related incoming mission task requests (mission request components). Hierarchy is further expanded, as an abstract planning KS (TaskRequestGoalGeneratorKS) triggers on each "TaskRequestAchieved" goal, generating a new set of "ElementaryTaskAchieved" subgoals. As stated in Chapter 2, corresponding elementary tasks (mission terminal nodes) refer to basic flight segments. Subgoaling further takes place at the next abstraction level, when new planning KS (ElementaryTaskGoalGeneratorKS) instances repeatedly trigger on "ElementaryTaskAchieved" goals. In that case, the KS action involves three coupled consecutive sequences of subgoal generation and problem-solving (child KSs) events. The three successive goal generation and problem-solving episodes include the following sequence: ("TaskPlanned", TaskPlannerKS), ("TaskDispatched", TaskDispatcherKS) and ("TaskValidationMonitored", TaskValidationMonitorKS). The associated KSs are respectively responsible for building a task plan, disseminating the computed plan and, validating the plan before and during execution. The child TaskPlannerKS currently constructs simple feasible plans by consecutively allocating legally admissible aircraft and crew resources. The execution of the next sequence is conditional on the success of the previous episode. Should a subgoal fail because no solution exists or plan repair (TaskReviserKS) does not succeed, the parent KS would be assumed to fail as well. Consequently, backtracking in the goal hierarchy, the control unit opportunistically would take a corrective action either by delaying parent goal ("ElementaryTaskAchieved") reposting it at a more suitable time if a plan cannot be computed or, promptly retrying the same parent goal (goal reevaluation) through an event-driven replanning KS (TaskReplannerKS) if the computed plan requires to be completely revisited. Feedback correlating expectations projected during the planning phase eventually leads plan execution to goal satisfaction, modifying the goal structure maintained by the control unit. The controller considers an abstract parent goal to be reached when all its child goals have been successfully achieved.

3.2.2.2 Monitoring:

Sensing and monitoring an evolving situation is crucial while constructing and/or executing action plans. Therefore, a multi-level monitoring scheme is proposed to ensure flexibility. High-level monitoring/sensing focuses on global situation changes whereas low-level monitoring limits its scope to plan execution. In both cases, significant change notifications to the blackboard are governed by monitoring control directives and parameters over selected state variable transitions reflected through database updates.

High-level monitors include the following event-driven knowledge sources: MissionMonitorKS, MissionTaskRequestMonitorKS, ResourceMonitorKS, WeatherMonitorKS and TaskTerminationMonitorKS. They consist in monitoring situation changes over domain areas (e.g. resources, tasks, weather, etc.) translating new mission and task requests, resource status, types and multiplicity, weather modifications or, plan execution outcome, respectively. High-level event-driven monitors are activated when meaningful change occurs over the database. Whenever feedback information does not match or deviate significantly from global expectations, the high-level monitor sends a message on the blackboard for deeper reasoning or impact assessment on current or predicted course of actions. For example, the unexpected earlier termination of a mission task is an important event not only to release resource and maintain blackboard consistency, but also to inform the blackboard control unit of the possibility to successfully address a pending mission request simply ignored due to a shortage of resource.

Low-level elementary task plan execution monitoring is achieved separately through TaskValidationMonitorKS knowledge source instances. Such a knowledge source determines over a certain time interval preceding plan execution if planned resource allocation is still feasible and likely to lead to the successful expected outcome. If pre-conditions no longer hold (e.g. resource failure), a message is sent on the blackboard and the monitor terminates.

3.2.2.3 Dispatching:

Action plan constructed and revisited dynamically over a rolling time horizon are disseminated to a tactical database to support human resource dispatching at a suitable time. Through a transaction manager service, a TaskDispatcherKS KS writes the computed task plan in the database and then, send a message to inform the user of the change. However, when an unexpected event monitored by a low level monitoring KS occurs, a TaskDispatcherKS KS is first invoked to delete/modify/update invalid information in the database.

Additional implementation details on the basic knowledge source mentioned above may be found in [9].

3.2.3 Human computer interaction

KARMA proposes some primitive form of mixed-initiative planning or capabilities to support human-computer interaction, a suitable property for any advisory decision support system component. Through a versatile human-computer interface, KARMA does provide the end-user with various options and the opportunity to partly accept, modify or reject recommended action plans. The user may also counter-propose action plans to the system. The proposed user interface has been designed to capture suitable information to supply from the computer to the user and how to interpret the information provided by the human's actions. Web-based capabilities shown by the KARMA user interface is also perceived as a key feature to support system learning and facilitate remote user interaction. Besides, KARMA shows additional flexibility regarding the distribution (static or dynamic) of authority between the person and the computer, the distribution of tasks to be addressed, the communication level desired between the human and the computer, and the principal value sought from the computer system, from active plan generation to more passive mission plan monitoring and authoring. More extensive implementation details may be found in [10, 11].

4. Demonstration

An experiment has been conducted to demonstrate the adaptive planning concept conveyed by the KARMA prototype. It consisted in participating in the international military Joint Warrior Interoperability Demonstration (JWID) exercise. The KARMA prototype has been successfully shown for the first time in JWID 2000 through animated demonstrations. Selected KARMA animations turned out to be a perfectly suitable instrument to draw some attention and raise enthusiasm for novel and useful decision support capabilities. Before the extremely positive feedback then shown by many operational and tactical Air Force organizations as well as the Chief of Defence Staff himself, the KARMA designer was invited by AFCCIS managers to actively take part to future JWID exercises. Consequently, the evolutionary KARMA prototype was fully demonstrated in military JWID 2001 [12, 13] and 2002 [14, 15] exercises.

4.1 JWID 2001

In JWID 2001, under the AFCCIS project supervision, some limited KARMA adaptive planning capabilities have first been demonstrated. AFCCIS kindly provided us with military personnel who were specially trained for the exercise. The main objective was to demonstrate an automated capability to support the adaptive planning concept. Accordingly, limited adaptive behaviors for dynamic tactical mission planning and repair, concurrent basic user interaction components (web-based and non web-based clients) and, parallel/concurrent process (user, system, database system) execution were specifically demonstrated. Another objective was to showcase KARMA interoperability with alternate system components. More details may be found in [16, 17]. The experiment was conducted using a two-thread scenario involving a coalition and a NORAD segment. The latter segment of the scenario involves a threat in the form of an unknown (possible drug trafficker) aircraft coming up along the eastern seaboard, which will move inland. Assets from a Fighter Squadron and a Tactical Helicopter Squadron are deployed as a quick reaction force in response to this event. Extensive details about the scenario may be found in [12, 16]. Interoperability involved heterogeneous interaction with two platforms, namely, WASP [18] and CASAP [19]. WASP is an authoring decision support system while CASAP (Commander's Advisory System for Airspace Protection) is a decision support system prototype supporting the analysis, comparison and selection of courses of action (COAs). Mission requests were automatically generated either by parsing and pre-processing air tasking orders (ATO) residing in the WASP database for the coalition segment of the scenario, or explicitly via CASAP messages through networked databases for the NORAD segment of the scenario.

The evolutionary KARMA prototype has been successfully demonstrated, as reported in [13]. Documentation quality and simplicity, a self-explanatory user interface and usability features to quickly describe and understand basic functions, as well as the non-existence of prior computer knowledge requirement to operate and interact with the system to efficiently acquire hands-on experience were particularly emphasized. In addition to showcase interoperability with alternate heterogeneous platforms, a key JWID objective and requirement, KARMA provides timely, cost-effective adaptive planning well beyond human capacity. Based on constructive user and visitors' comments recognizing the relevance and potential usefulness of KARMA for real tactical operations, it became obvious that the system could be applied to a variety of military (fighter planning, maritime air fleet, transport fleet planning, etc.) and non-military domains. However, given overenthusiastic JWID participants and visitors, the report indicates that additional developmental work based upon a more extensive work analysis would be required to improve KARMA and bring the prototype to an acceptable level of deployment. Accordingly, a more comprehensive user interface providing additional valuable information to the user, and the explicit modeling of maintenance requirements (e.g. stagger) and constraints imposed on resources would be very useful or required to improve the planning process.

4.2 JWID 2002

In JWID 2002, concept demonstration has been extended to a coalition environment. Under the COP21 [20, 21] project supervision, it mainly aimed at demonstrating the adaptive planning concept to a limited coalition context through a distributed collaborative planning experiment. The COP21 Technology Demonstration project refers to the broad concept of "Common Operational Picture" which consists in enabling commanders to share a common view of the battle space and provide essential information to subordinate staff to achieve planning and conduct operations [14]. The interest of COP21 toward KARMA lies in the development and demonstration of advanced commander’s decision support capabilities to effectively plan and direct CF operations.

The KARMA experiment was primarily designed to handle key steps of the operation planning process in demonstrating adaptive planning capabilities to timely support centralized coalition resource planning, monitoring and control [22]. A non-combatant evacuation operation (NEO) scenario [14, 23] involving multiple nations (US, UK, Australia and Canada) interacting over a coalition force network and sharing locally homogeneous resources (helicopters and pilots) was considered. In that setting, a single vehicle (helicopter) depot and its related crew personnel are associated to each coalition member. Mission requests submitted to KARMA were generated through COPlanS (Collaborative Operational Planning System) [24], a system prototype mediating the distributed decision-making process leading to a common course of actions. In a closed-loop environment, KARMA scheduled relevant tasks of coalition airlift operations deliberating on coalition member assignment and related resource allocation. Problem complexity was slightly reduced, as member nation depots were first assigned based on minimum distance during mission plan computation. Resource availability at local depots then finally determined plan feasibility.

The evolutionary KARMA prototype has been demonstrated in a limited coalition environment successfully providing a plan development and operations scheduling capability [15]. It computed real-time mission plans incorporating multi-national resources, and provided an improved web-based user interfaces to support on-line coalition member interactions while ensuring interoperability with the CO-PLANS platform. As a separate component that can be tailored to specific environments and further integrated or interfaced to larger decision support or command and control information systems at low cost, KARMA shows attractive dynamic planning features applicable to a wide range of domains.

5. Discussion

Despite the risk and complexity of designing automated advisory decision support system to address major challenges and limitations shown by current systems, the advanced adaptive planning concept satisfactorily demonstrated through the KARMA prototype clearly paves the way to further planning investigation in dynamic uncertain environments and major foreseeable economic savings. KARMA successfully addressed system limitations shown by recent decision support system prototypes (e.g. WASP, DSS, TBMCS) providing automated decision support capabilities, flexible closed-loop dynamic planning and execution monitoring well beyond human capacity, mixed-initiative planning and user assistance capabilities on a continual basis. Control can be handed over back and forth from the system to the user and vice versa at user's convenience relieving the user from demanding task overload while guaranteeing end-to-end plan execution monitoring and automatic plan repair. Based on the scenarios explored so far, the system appears reasonably fast and responsive, performs reasoning tasks timely and shows graceful adaptation, distancing itself from traditional and very limited authoring tools usually targeted to military organizations and services such as 1 Wing, 8 Wing and squadron units. It is believed that further but modest efforts directed toward more suitable user interfaces might significantly contribute to promote visibility and utility of the underlying KARMA technology, and ultimately lead to wider acceptance by the user community. Applicable to other problem variants and classes, the KARMA concept can also be extended and taken one step further to naturally address "distributed continual planning" in which multiple autonomous decision makers must collaborate and cooperate, successfully achieving team coordination in meeting a variety of common and private goals. Alternatively, additional short-term benefits might be expected by exploring the integration of the technology to existing domain-independent decision-making components or enhancing new support capabilities to key user tasks such as tutoring and training.

6. Conclusion

A knowledge-based adaptive resource management agent to support closed-loop dynamic planning and execution monitoring control in a time-constrained uncertain military environment has been presented. Based on parallel blackboard architecture, the proposed solution emphasizes the concept of adaptive planning. Using specialized knowledge sources whose execution is mediated by a mixed goal-directed and data-driven control unit to timely carry out planning and monitoring tasks at various abstraction levels, KARMA has been applied to an Army Aviation Fleet context, namely, the Tactical Helicopter Squadron mission planning problem domain (air vehicle routing and crew scheduling). Further system enhancements did include mixed-initiative planning capabilities to support human-computer interaction. The KARMA prototype has been successfully demonstrated in international military JWID exercises.

Future work will explore system transition to major ongoing activities while possibly directing further research efforts based on emerging opportunities. The commander's decision support segment of the COP21 project is an obvious target. Discussions on a technology transfer through an evolutionary process to the Air Force Command and Control Information System (AFCCIS) project have been initiated and are still ongoing. The proposed KARMA technology concept demonstrated within the Army Aviation Fleet context (tactical level) clearly shows its applicability to alternate military domains and components as well, including Fighter Fleet, Air Transport Fleet and Maritime Air Fleet activities to name a few. Should military interest be sufficient to explore different advanced technology concepts while concurrently supporting targeted limited trials, future work would include further investigation on key research areas such as distributed collaborative continual planning, learning (tutoring, planning, coordination, etc.) and human-agent interaction (construction of users models including beliefs, misconceptions and preferences; explanation of system actions, on-line aiding, tutoring).

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A knowledge-based adaptive resource management agent (KARMA) to support dynamic planning and execution monitoring control in a time-constrained uncertain military environment is presented. Based upon a parallel blackboard architecture, KARMA relies on the concept of adaptive planning which interleaves plan construction and plan execution allowing accurate planning when time is available and coarse fast planning under time pressure, trading-off solution quality and run-time computation. The adaptive planning concept shown by the KARMA prototype has been applied to an Army Aviation Fleet context, namely to a tactical squadron domain level to support mission planning (air vehicle routing and crew scheduling), and clearly shows applicability to alternate military domains and components as well.

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