An Architecture for Real-Time Mixed Initiative Collaborative Planning

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Abstract

This paper describes an architecture for real time tactical planning in a naval combat system. Based around multiple users sharing a real time mixed initiative planning server, this system allows several specialists to collaboratively interact with the computer under the supervision of a task leader. Since the tactical domain requires real time response to high priority events, planning control passes between the specialists, the supervisor, and the automated planner as a function of changes in the environment. This architecture has been implemented in the DARPA Ship Systems Automation (SSA) Tactical Planner.

Introduction

Controlling a naval vessel is a complex real-time task which involves multiple teams of operators controlled by a hierarchy of supervisors. At the top of this hierarchy is a team consisting of the Tactical Action Officer (TAO), who is in overall command, and a group of specialists including a ship control officer, an undersea warfare (USW) coordinator, an anti-air warfare (AAW) coordinator, etc. This command team analyzes the tactical picture, cooperatively constructs a plan for dealing with that picture, and supervises the execution of that plan.

The collaborative planning of the command team functions by the specialists drafting plans to deal with the problems in their areas of specialization, then the TAO merging those plan fragments into a coherent, conflict-free whole. Where the fragments conflict too much to merge, the TAO may direct the effected specialists to revise their plans based on additional constraints, and then repeat the process until an executable plan emerges.

This system worked well when navies focused on fighting on the high seas, where radars could scan to the horizon and telling friend from foe was relatively simple. With the end of the Cold War the focus of naval operations has shifted to coastal waters such as the Persian Gulf, which are busy with neutral traffic and typically provide a complex, high clutter environment for sensors such as radar. In this high ambiguity environment separating friend from foe from neutral is very difficult. Furthermore, the complex environment affords attackers opportunities for surprise, so the engagement timelines are drastically shortened by threats "popping up" from the clutter.

To survive and maintain combat effectiveness in this coastal or "littoral" arena, the command team needs to analyze larger amounts of data, and plan and implement appropriate responses faster than ever before. The work described in this paper is on a multi-user real-time mixed-initiative planning system which supports the work of the command team in determining the most appropriate responses to the tactical scene, integrating them into a coherent, executable plan, and then executing that plan. We briefly describe the planning engine which makes this possible, and the collaborative architecture in which it is embedded. Then we summarize the experimental application of this mixed-initiative multi-user planning system on the DARPA Ship Systems Automation program.

Planning Architecture

Over the past seven years a series of prototype planners have implemented and an architecture has evolved to address the naval command and control problem. Starting with a relatively straight-forward rule-based submarine torpedo defense planner (Sublette & Vainshtein 1991), increasingly strict real-time constraints and increasingly complex multi-warfare test scenarios forced the planners to evolve into the current mixed-initiative hybrid architecture.

The Planning Server

The plan server architecture is a blackboard system organized as a hierarchical task network (HTN) decomposition planner (Wilkins 1988). The planner combines both reactive and deliberative planning elements. It uses case recognition and retrieval to select the tasks to be executed in the current tactical situation. These tasks are organized into a partially-ordered HTN according to the threat priorities assigned by the situation assessment system, and are passed to appropriate planning methods together with the associated tactical situation data (tracks, sea state, wind speed and direction, current course, speed, etc.). The methods, which often compete with each other for ship resources, are invoked in the order specified by the HTN. This ordered invocation allows methods for higher priority tasks to pre-emptively tie up scarce resources, leaving lower priority methods to plan around the resulting resource constraints. The methods decompose the tasks into further method calls until the planner is dealing either with simple actions or with pre-defined combinations of such actions, referred to as *tactics*. At this level models are called to compute the parameters of the actions such as maneuvers, sensor schedules, etc.

Once all of the methods have run, the planner assembles all of the plan fragments generated by the various methods into a coherent plan for execution. Where conflicts are detected despite the prioritization process described above, the planner alerts the operator and asks for assistance in deconflicting the plan, typically by operator adjustment of the tasking constraints and priorities. Once an executable (i.e. conflict-free) plan is constructed, a multivariate utility function is used to evaluate the plan.

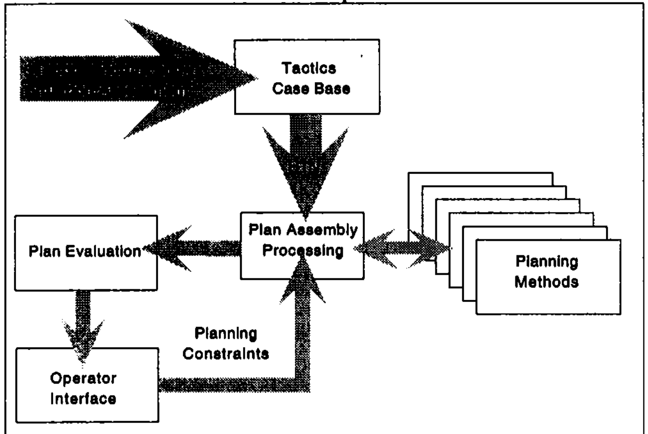

Figure 1.Architecture of Plan Server

Typically multiple plans are generated to deal with different hypotheses about the tactical situation. These hypotheses may be alternate scene interpretations generated by the situation assessment team, or potential evolutions of the scene postulated by the operator of the planner. Currently the plan server presents all of these plans to the operator, and designates the plan associated with the highest likelihood scene interpretation as the default. If the plan does not involve pre-approved actions, the preferred plan and its evaluation is presented to the operator for approval. Otherwise, the pre-approved elements of the plan are placed into execution (with the opportunity for operator command by negation), while the plan as a whole is presented for consideration. In either case, once approval is received the plan is placed into execution, replacing the previously executing plan.

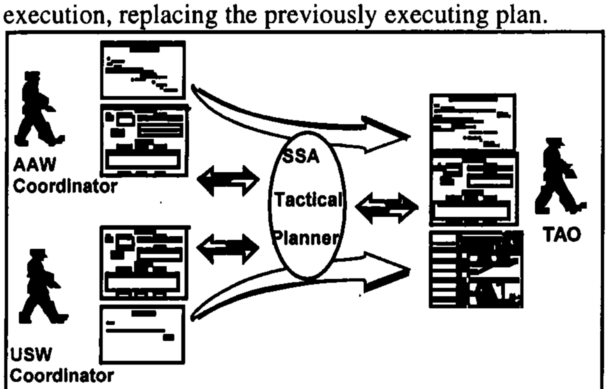

Figure 2. Computer Mediated Multi-User Planning

During plan execution the system continuously monitors both the tactical environment, and the effects of its actions on that environment. In this domain there are many agents changing the environment, some independently and some in collaboration. Furthermore, the actions of each of these agents are of uncertain effect. Any of these things can cause a plan to break, and force replanning. When a plan breaks, the planner seizes the initiative and replans based on the new situation and the current default constraints. This new plan is presented with an alert to the TAO which identifies the reason for the replan.

Use of the Plan Server to Support Multiple Users

Given the ability of the plan server to construct a plan under all of the time varying constraints described above, one is still left with an organizational problem. In current naval command and control systems there is a team of operators who manage different parts of the tactical situation under the control of the officer in charge. Even assuming the plan server can construct plans to satisfy each of these specialists, the problem of coordinating the various Warfare area coordinators and fusing their warfare area plans into a coherent whole for evaluation and modification by the TAO remains.

The approach taken is to use the plan server described above to mediate the multi-user planning process. Since the plan server can generate multiple plans in real time, each warfare area coordinator invokes the plan server with his or her own set of planning constraints to generate plans for their warfare area. These constraints include guidance from the warfare area coordinator and TAO-imposed constraints which limit the individual warfare area coordinator's use of ship resources. The warfare area coordinators individually interact with the plan server in the mixed-initiative manner described above. This interaction may include both plan construction cycles against the actual tactical scene, and against hypothetical extensions of the scene. When a coordinator is satisfied with their current warfare area plan and wishes to place it into execution, the system passes the associated planning constraint set to the TAO. He or she interacts with the computer to merge that set of planning constraints into the larger set used to generate an integrated plan for the whole ship. This merging process allows the TAO to balance the demands of the various warfare areas within the overall tactical context. The merged planning constraint set thus generated is the starting point for an interactive planning cycle involving the TAO and the plan server. If an acceptable integrated plan can be constructed, the TAO approves it and places it into execution. If not, he might levy additional constraints on some or all of the warfare area coordinators, and iterate the process at that level again.

This planning/executing/planning cycle continues throughout the mission. As discussed above, this cycle is subject to arbitrary interruptions as the tactical situation unfolds and as the initiative passes back and forth between the human operators and the automated planning and situation assessment systems. Plans, queries, explanations and justifications are constructed for time varying real and hypothetical tactical scenes, and plans are continually executed, monitored, and replanned in an intricate dance of human operators, computers, software agents, and objects and actors in the real world.

Experimental Results

The current prototype mixed-initiative planning system performed in real time as part of the 1996 Advanced Combat System Demonstration of the DARPA Ship Systems Automation program. This demonstration involved several intelligent software agents collaborating with each other and a varying number of human operators on a simulated DD-963 type surface combatant in a challenging transition-to-war scenario set in the approaches to the Persian Gulf. The planning system interactively provided both "real-world" and hypothetical combat operations planning throughout the one hour scenario. In this configuration the plan server was able to generate an integrated multi-warfare plan in less than 500 milliseconds on a Silicon Graphics *Indigo II* workstation.

Related Work

Given the combinatorial nature of generative planning, considerable research has focused on finding alternatives which are better behaved. A recent thread of research relevant to the current work is case-based planning (Blau, Bonissone & Ayub 1991). Another relevant approach to bounding the computational requirements of planning is hierarchical task network decomposition. Whether done top-down (Erol, Hendler & Nau 1994) or bottom-up (Barrett & Weld 1994) it provides a powerful method for controlling the adaptation of plan cases.

Decision theory is concerned with making rational decisions in an uncertain world. As uncertainty is one of the few constants in combat, decision theory is a useful tool for planning actions in the tactical domain (Horvitz, Breese & Henrion 1988). It is being applied to cooperative tactical planning by (Cook, Gmytrasiewicz & Holder 1996) and (Gmytrasiewicz & Durfee 1992).

The general problems of the naval command and control domain, along with some of the technologies being developed to deal with them, are discussed further in (Brander & Bennet 1991) and (Mitchell & Corcoran 1995).

Acknowledgments

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