Mission Planning for Autonomous Systems

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1. Abstract

Planning is a necessary task for intelligent, adaptive systems operating independently of human controllers. In a mission planning system that performs task planning by decomposing a high-level mission objective into subtasks and synthesizing a plan for those tasks at varying levels of abstraction. We use a blackboard architecture to partition the search space and direct the focus of attention of the planner. Using advanced planning techniques, we can control plan synthesis for the composite planning tasks involved in mission planning.

2. Introduction

Planning is a necessary task for intelligent, adaptive systems operating independently of human controllers. Autonomous systems need to plan their actions and adapt to environmental changes for survival. Given a high-level mission specification, the mission planning module needs to synthesize a sequence of actions to achieve mission goals. This requires advanced techniques that reason about constraints, granularity of search, spatial configurations, levels of abstraction and temporal orderings. Robotic systems benefit from these planning techniques by increasing their independence from mission control. As a result, expanded missions with reduced supervisory control can be envisioned and executed.

Various approaches are being used in planning systems. STRIPS uses means-ends analysis in robotic problem solving by identifying differences from a state description to a goal and selecting forward production rules to reduce them. NOAH uses levels of abstraction and a least-commitment strategy to generate parallel plans hierarchically for an air traffic control system. BPM uses opportunistic planning to solve the control planning problem by combining both top-down and random sampling planning activities. MOLGEN uses general refinement of plan experiments to incorporate flexible reasoning by reusing specific operations from a sequence of generalized plan steps. PROTEAN uses a blackboard architecture to configure planning structures by reasoning about the context of the system as well as the problem-solving process. Our mission planner builds on these earlier systems and uses expert systems techniques. It is implemented within the 3B1 blackboard architecture and uses the features offered by 3B1.

3. Mission Planning

The overall control of autonomous systems requires the management of multiple subsystems cooperating to achieve mission goals. One such subsystem is a mission planner. This paper reports on a mission planning system built for the autonomous operation of FMC's autonomous and vehicle in M113 tracked vehicle.

Mission planning is the process of synthesizing a sequence of actions to satisfy goals and constraints posed by the mission manager. Mission plans are specified at varying levels of abstraction, with mission profiles at the higher levels and command sequences at the lower levels. Command sequences are fixed to perform specific tasks given the vehicle's operating characteristics, such as when they are best executed by computer programs that perform table lookups. Contention among these commands can usually be resolved at the higher levels; thus interaction among commands is minimal. At the lower end of the planning hierarchy, mission profiles specify objectives and time tables for accomplishing the objectives. The vehicle achieves these objectives by executing commands downloaded by Mission Control at the appropriate times specified in the mission profile. Mission profiles lend themselves to template or script planning because they are specified at a level of detail higher in the interaction hierarchy where interaction among the objectives is minimal.

Tasks, on the other hand, are synthesized into plans by considering the current state of the mission. Tasks consist of command sequences an autonomous vehicle executes to achieve some part of the overall mission. The planner performs task planning by decomposing the high-level mission objective into subtasks and synthesizing a plan for those tasks at varying levels of abstraction. Intermediate tasks must be selected and sequenced in such a way that subsequent goals can be achieved. An exemplary task performed by the planner is to develop a plan for conducting reconnaissance in a particular area specified by the mission commander. For example, a mission to conduct area reconnaissance is necessary when the commander desires specific information about certain locations or facilities within a defined area. To accomplish this mission, the planner must find overwatch positions for reconnoitering the target, establish routes approaching those positions, return status of the operation and report all information rapidly and accurately.

Tasks refer to the intermediate abstraction levels in the planning hierarchy, some levels where interaction among planning objectives is the highest. Interaction among tasks is either by sequencing tasks with prerequisite and prequalitative conditions or by decomposing tasks into subtasks that occur as a result of the interesting planning problem. These interactions occur in a dynamically changing environment and create a nondeterministic explosion of the planning space. The search through this dynamic planning space is a key issue for mission planners.

4. Blackboard Architecture

We are implementing our mission planner using MESS, a Blackboard Event-Driven System, a version of the 3B1
blackboard architecture. As such, it defines problem-solving knowledge sources for synthesizing plan steps, a multi-level solution blackboard for recording partial plans and a flexible control structure for controlling the expansion of the planning space.

Using a blackboard, a hierarchy of execution levels where each level represents a partial state description of the world at some time, we can partition the search space and direct the focus of attention of the planner. We map the problem space onto the blackboard by specifying abstraction levels in the plan hierarchy. These levels represent both strategic and conceptual abstractions for the mission planning problem. For the mission of area reconnaissance, we generate a viability map by creating boundary regions that contain locations visible to the target—a spatial abstraction. For the path planning task of the mission, we generate one type of non-traversable region by creating water bodies—a conceptual abstraction.

Data abstractions help control the exponential search process required in planning by establishing planning schemas where local search can find plan anchors for attacking the remainder of the plan. The more independent the planning schema, the better the planner controls the planning space by relying on local search. The blackboard structures the planning space in the problem domain. To this structure, we apply the problem-solving strategy of skeletal plan refinement.

When a mission is specified, the planner chooses a general design. We specify a design with only the essential details necessary to direct the initial search of the plan. The least-commitment strategy is maintained throughout the plan refinement process. The design specifies spatial configurations for planes and partitions the planning space into plan segments. Once these segments are found, the planner successively refines its plan by instantiating plan steps at the lower levels. Plan instantiations occur by creating planning elements using the correct data abstraction with the current plan abstraction. At the design level, the planner cannot use low-level data to form decisions. Instead, it uses high-level symbolic objects that represent the relationships between the tasks that make up the mission.

For example, consider a plan for a reconnaissance mission that synthesizes a sequence of tasks in both time and space such that the final plan constitutes an traversing objective. A good design specifies the spatial orientation for each of the tasks. Finding this design depends on the reconnaissance tasks involved and their relationships to each other. At this level, the planner reasons about the target location, the type of reconnaissance mission, visibility maps, non-traversable regions, military strategy and communication requirements. Only after refinement of the design can plan steps involving task set tasks be instantiated using plan data represented as coordinate tuples.

4.1 Controlling Plan Synthesis

Plan synthesis occurs when knowledge sources instantiate plan steps recorded in the blackboard hierarchy. Without controlling plan synthesis, the planning system would successively create the solution space of possible plans. While the system works for simple planning problems, in mission planning, as the complexity of the mission increases, the number of tasks grows and the number of potential plans grows exponentially. We use a three-tiered structure for varying control over the execution of knowledge sources in the mission planning system that consists of establishing focus decisions, executing strategies and ranking knowledge sources. During problem solving, knowledge sources create decision elements in the plan hierarchy—e.g. planning proposals—knowledge sources are activated and become available for execution. A controller rates these knowledge sources using focus decisions, strategies and rankings, and a scheduler selects a knowledge source to execute by choosing the one with the highest rating.

Focus decisions represent collections of heuristics against which knowledge sources are rated. These decisions establish criteria used to evaluate the utility of knowledge sources. For each knowledge source the controller calculates a utility value by summing together, for each focus decision, the product of a focus weight representing the value of a focus decision and a satisfaction level, the degree to which a knowledge source satisfies a focus decision. This calculation results in ratings that prioritize the knowledge sources so a scheduler can select the knowledge source with the highest rating. Focus decisions are created during problem solving in response to changes in planning and reflect the general behavior of the system. They add high-level control decisions that the controller uses to direct the generation of plan steps.

Strategies provide a rigid control structure that directly controls the execution of knowledge sources. They permit the execution of a strict sequence of knowledge sources. A strategy represents a procedure for reaching a particular goal and consists of a goal, a status, a rationale and a list of strategies and tactics. The goal denotes what the strategy will accomplish when its status becomes operative, and the rationale describes what the strategy accomplishes. An ordered list of strategies and tactics defines the specific subgoals that make up the procedure. When strategies are operative, knowledge sources that achieve the same goals of the operative strategies receive higher priorities than ones that achieve different goals. Focus decisions are used to differentiate between knowledge sources with the same goal.

Figure 4.1 illustrates the structure of two strategies used by the Mission Planning System. The first strategy, FIND-LOCATION, consists of three tactics: INSTANTANEOUS-LOCATION, RATE-LOCATION and CHOOSE-BEST-LOCATION. The strategy finds a location by creating instances of locations, rating them and choosing the best one. The second strategy, FIND-RI, consists of the tactic INSTANTANEOUS-LOCAL-AREA-RI and the strategy FIND-LOCATION. This recursive definition facilitates creating new strategies from existing ones. This strategy finds a location for performing reconnaissance by creating instances of local areas near target locations within these areas.

The third level of control in the three-tiered structure, ranking knowledge sources, overlaps with the proceeding two. Ranking prioritizes knowledge sources that are grouped together because of similarities in function or strategy. During system design, knowledge sources are ranked to differentiate between instances in their performance characteristics, usually by performance factors and processing speeds determining the granularity of search. Ranking gives the controller a discriminating factor when it chooses among knowledge sources with the same rating. Thus, ranking determines between knowledge sources that
would otherwise be considered equal. Knowledge sources with the special rank of IMMEDIATE bypass the controller and execute immediately.

5. Constraint-based Reasoning

Another technique for controlling search is using constraints to limit the number of acceptable plans. Our planner uses constraints based on terrain feature information, resource limitations, vehicle limitations, and military doctrine. In this way, the space of possible planning solutions is constrained by the specifications of the mission requirements. A mission must meet certain objectives while satisfying constraints that limit the success of an operation. The harder the constraints, the less flexible the plan and the easier it is to confine the search. As constraints become softer, they contribute less to confining the space of possible plans. Our mission planner uses hard constraints to limit the number of acceptable plans by reasoning about terrain feature information, resource limitations, vehicle limitations, and military doctrine during the planning process.

Mission planning at a data manipulation; therefore, search must be performed using different levels of granularity. We use a strategy that satisfies hard constraints before considering the soft constraints. Failure to satisfy any of the hard constraints results in the planner either terminating its search or backtracking by considering new potential solutions. Our planner performs simple backtracking by expanding the search through the data tree. By continuously increasing the resolution of the search, the planner increases the number of data points that it considers during planning. This technique allows the planner to make uniform cuts through the planning space. The planner performs more complicated backtracking by modifying constraints, thereby achieving the objective but with some loss of optimality. The planner relieves constraints by propagating hard constraints. In our example of a recon mission, an original constraint can be the reconnaissance technique of triangulation. However, when this constraint cannot be satisfied, the system relaxes it into one that allows straight recon. The constraint remains a hard constraint, but it must be satisfied to complete the mission, but a plan allowing for straight recon is less desirable than the original triangulation.

Our planner works first from hard constraints to find a solution and backtracks only when necessary. It uses soft constraints, but considers them with less priority. Using constrained search, we confine the planning space to one that satisfies the hard constraints, then find a solution that satisfies most of the soft constraints. As an example, consider the problem to place different sized objects in a leather pouch. A more common strategy places the larger items in first, then squeezes the smaller ones. This strategy works well because the planning space is characterized by the capacity of the leather pouch. Mission planning has a similar planar planning space because missions are defined to maximize changing conditions that occur during the execution of a mission. Thus, we use a strategy that satisfies the hard constraints, much like placing the larger items in the leather pouch first, then squeezing the soft constraints into place.

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Our plan, in this case, is to use the A1-22 strategy of recon mission, which is based on reconnaissance techniques and mission constraints. The planner implements this strategy and a selected mission and task set is matched against the available vehicles. A mission is selected based on the requirement for reconnaissance that identifies the tasks necessary to accomplish the mission. These tasks are combined to a mission that is decomposed into vehicle and terrain constraints. With the mission completed, the start and goal locations are matched with references by the planner. A plan resulting in a recon mission using triangulation is selected and a strategy for instantiating the script is generated. Here, the planner implements the A1-22 strategy.
Having generated a strategy, the planner can instantiate lots, levels, and areas where the planner searches for reconnaissance locations. It then finds lookout and rendezvous locations to move those elements into the final plan.

Figure 6-2 shows the planning state after the planner has found one possible plan for performing area reconnaissance using triangulation. The final plan is represented as nodes at the Location and Rendezvous levels. In this "as-is" plan, the vehicle travels along ROUTE1 from its starting position to the first reconnaissance location, R1. After reconnoitering the target, it travels along ROUTE2 to the second reconnaissance location, R2. At this point, the vehicle triangulates data acquired from the first reconnaissance task and completes the mission by moving to its final destination along ROUTE2.

7. Construction

We have built a Mission Planning System capable of sequencing units to achieve higher level mission objectives. We have built this system using a blackboard architecture that defines knowledge sources, a multi-level blackboard and a flexible control structure. Using this architecture, we have integrated with other planning techniques, we have some degree of control over the explosive search space inherent in mission planning problems.

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References


