1. Abstract
Planning is a necessary task for intelligent, adaptive systems operating independently of human controllers. In a mission planning system, tasks are decomposed into subtasks and synthesized into 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 complex 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 themselves 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 observed and executed.

Various approaches are being used in planning systems, STRIPS uses means-ends analysis in robot 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 aiding module [3]. BPM uses opportunistic planning to solve the tactical planning problem by combining both启发式 and state-based planning activities [4]. MOLGEN uses general refinement of plan experiments in molecular biology by establishing specific operations from a sequence of general operations [5]. PROTEAN uses a blackboard architecture to configure protein structures by reasoning about the system as well as the problem-solving process [6]. Our mission planner builds on these earlier systems and uses the features from each. It is implemented within the 3BI Blackboard Architecture [7] and uses the features offered by 3BI.

3. Mission Planning
The overall control of autonomous systems requires the management of multiple sub-systems interacting to achieve mission goals. One such sub-system is a mission planning system. This paper reports on a mission planning system built for the autonomous operation of FMC's autonomous vehicle, an MT13 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. Mission sequences are fixed when performing specific tasks given the vehicle's operating characteristics as well as their current state. Mission sequences can 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 command sequences 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, in the other hand, are synthesized into plans by considering the current state of the mission. Tasks consist of a sequence of command sequences as 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 these 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 a 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 reconnaissance, select the target, establish routes, select these positions, record results of the operation and report all information rapidly and accurately.

Tasks refer to the intermediate abstraction levels in the planning hierarchy. These levels where interaction among planning decisions is the highest. Interaction among tasks may vary when sequencing tasks with prerequisite and postprerequisite conditions or by decomposing tasks into subtasks makes up the interesting planning problem. These interactions occur in a dynamically changing environment and create a combinational 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 3BI, a Blackboard Event Driven System, a version of the 3BI
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 instruction 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 spatial 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 landmarks where local search can find plan anchors for attaching the remainder of the plan. The more independent the planning landmarks, the plan controller 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 detail 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 the plans and partitions the planning space into plan segments. Once these segments are found, the planner successively refines the 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 with time and space such that the final plan satisfies the mission's overriding objectives. 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 of abstraction, 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 task locations be instantiated using task data represented as coordinate triples.

4.1. Controlling Plan Synthesis
Plan synthesis occurs when knowledge sources instantiate plan steps recorded on the blackboard hierarchy. Without controlling plan synthesis, the planning system would sequentially create the solution space of possible plans. While this 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 decision, executing strategies and ranking knowledge sources. During problem solving, knowledge sources create decision elements in the plan hierarchy—ie planning requires more 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 as responses 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 achieving 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. The 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 goals.

STRATEGY: FIND-LOCATION

* goal = FIND-LOCATION

* status = OPERATIVE

* rationale = "Instantiates best location for performing a task"

* strategyDecision = (INITIATE-LOCATION RATE-LOCATION CHOICE-LOCATION)

STRATEGY: FIND-R1

* goal = FIND-R1

* status = OPERATIVE

* rationale = "Controls search for R1"

* strategyDecision = (INITIATE-AREA-Area-R1 FIND-LOCATION)

Figure 4.1: FIND-LOCATION and FIND-R1 strategies.

Figure 4.1 illustrates the structure of two strategies used by the Mission Planning System. The first strategy, FIND-LOCATION, consists of three tactics: INSTANTIATE-LOCATION, RATE-LOCATION and CHOICE-BEST-LOCATION. This strategy finds a location by creating instances of locations rating them and choosing the best one. The second strategy, FIND-R1, consists of the tactic INSTANTIATE-LOCAL-AREA-R1 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 locations in areas within these areas.

The third level of control in this 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 strategies in their performance characteristics. Usually, performance factors are overlapping speed with processing speed 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 planners use 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 confuse 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.

Missions planning a data intensive; 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 these constraints results in a plan that either terminates 1st search or backtracks by considering new potential solutions. Our planner performs simple backtracking by expanding its search through the data base. By continually increasing the resolution of the search, the planner increases the number of data points that it considers during planning. This technique allows it to make uniform cuts through the planning space as it refines plans top-down through the plan hierarchy. The planner performs more complicated backtracking by modifying constraints, thereby achieving the objective but with some loss of optimality. The planner relaxes constraints by propagating hard constraints via an example of a reconnaissance mission, an example of how the reconnaissance technique works. However, when the constraint cannot be satisfied, the system relaxes it into one that allows for straight reconnaissance. The constraint remains a hard constraint and must be satisfied to complete the mission, but a plan allowing for straight reconnaissance is less desirable than one that uses translocation.

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 define the planning space to one that satisfies the hard constraints and 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. An effective, simple strategy places the larger items in first, then spaces in the smaller items. This strategy works well because the planning space is characterized by the insufficiency of the leather pouch. Mission planning has a similar flexible planning space because missions are defined to maintain 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 spaces the soft constraints into place.

- Hard constraints refer to those constraints that must be satisfied when finding a valid solution.
- Soft constraints refer to those constraints that may or may not be satisfied when finding a valid solution.

6. Mission Planning Results

The Mission Planning System was written in Zetas, an on a Symbolic Lisp Machine and interface to other software modules needed to control FMC's autonomous land vehicle. The planning system consists of 102 domain knowledge sources, 5 control knowledge sources, 27 strategies, and 17 tactics.

Figure 6-1 shows the planning state at the Mission Planning System in the intermediate stages of finding a plan for conducting reconnaissance. In this example, the planning system requests a plan to recommission an area using translation techniques that gather information about the target. It synthesizes a plan by executing knowledge sources and posting information on the blackboard. The blackboard levels are shown from the strategy level down to the Route level. Strategies, Tactics, and Plans make up the Control Blackboard, while Mission, Domain, Region, Script, Lot, Location, and Route make up the Domain Blackboard. Values are depicted in one of four states: underlined values represent preoperative criteria that the planner considers when making decision values shown in reverse-video denote the current activated subgoals in the planning space; boxed values are the selected positions and routes that make up the final plan; and shaded values use (figure 6-2) depict goals that have been accomplished.

Figure 6-1: Mission Planning State in Cycle 21

Figure 6-2: Mission Planning State in Cycle 32

After receiving a mission statement from the commander of the vehicle, the planning system requests to find a possible plan. It starts by creating fuses that provide top-down control. This behavior changes to the system operator and creates other control decisions. A script is selected based on the requirement for triangulation that identifies the tasks necessary to accomplish the mission. These tasks are confined to a region that is computed based on vehicle and terrain constraints. With the region computed, the start and goal locations are posted for reference by the planner. A script resulting in 25 strategies is selected and a strategy for instantiating the script is presented. Here, the planner implements the RT-R2 strategy.
Having generated a strategy, the planner can instantiate the final plan. A level
measuring the planner searches for reconnaissance locations. It then finds
locations and routes and sequence them into the final plan.

Figure 4-2 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 Route levels. In this case, the car travels along
ROUTE1 from its starting position to the first
reconnaissance location, R1. After reconnaissousing the target, it
travels along ROUTE3 to the second reconnaissance location,
R2. At this point, the car triangulates data acquired from the first
reconnaissance task and completes the mission
by moving to its final destination along ROUTE2.

7. Conclusion

We have built a Mission Planning System capable of
sequencing tasks 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 integrated
with other planning techniques, we have some degree of
control over the expensive search space inherent in mission planning
problems.

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