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# ARCHITECTURE FOR SPACECRAFT OPERATIONS PLANNING

William S. Davis
Boeing Computer Services
Artificial Intelligence Center
PO Box 240002, MS JA-74
Huntsville, AL 35824


## *ABSTRACT*

The dynamic environment of working in space presents several challenges to planning space operations. One challenge is the heterogeneous nature of the operations to be performed, ranging from life science experimentation to vehicle assembly. Generating plans for such diverse tasks requires a system that exhibits many domain-independent characteristics. A second major challenge is that the performers of these operations (plan agents) are also heterogeneous, possessing varying skills and physical capabilities. In this regard, planning must be possible both separately from, and in consideration of, each agent's capabilities, whether crewmember or robot. Finally, operating in space encompasses unanticipated events. By definition, no pre-established (or "canned") plan can accommodate.such situations; hence a system is required which can dynamically plan and replan according to evolving knowledge.

We present such a system which generates plans for the dynamic environment of space operations. This system synthesizes plans by combining known operations under a set of physical, functional, and temporal constraints from various plan entities (agents, objects, tasks), which are modeled independently but combined in a flexible manner to suit dynamic planning needs. This independence allows the generation of a single plan source which can be compiled and applied to a variety of agents. Another result of this modular planning concept is the ability to generate different plans from the same instructions, according to the objects used in the plan. The architecture blends aspects of temporal logic, nonlinear planning, and object-oriented constraint modeling to achieve its flexibility. In our operations testbed, we have applied this system to the domain of IVA maintenance and repair aboard Space Station Freedom, planning operations for (1) a crewmember, generating English statements and interacting using speech synthesis and voice recognition systems; (2) a one-armed robot, generating robotic programming instructions for sequential actions; and (3) a graphical simulator, generating software commands for a NASA/Vanderbilt simulator modeling one- and two-armed robots.




## 1. Introduction

The domain of mission operations, as applied to spacecraft such as Space Station Freedom (SSF), is characterized by both long life cycles and a broad scope of activities. For example, Space Station Freedom is expected to perform orbital operations for approximately thirty years, during which it will serve a variety of both scientific and space exploration needs. Scientific activities vary in types of experimentation, including life sciences, materials processing, astronomy, automation and robotics, and other disciplines applying primarily to spacecraft operations. Space exploration includes the orbit-based activities of assembling, testing, servicing, launching, and recovering spacecraft (Lunar and Mars Transfer Vehicles) and the surface-based activities of navigation, experimentation, and outpost establishment [1]. In addition, routine activities (housekeeping, maintenance, repair) must be performed for each craft to maintain proper operating status of its components.

## 2. Planning Issues Associated with Spacecraft Operations

A recent NASA/OAST study has indicated a long-term research focus on intelligent agents to support automation for space exploration [2]. Planning for these intelligent agents, however, faces challenges created by properties inherent to the domain. First, the tasks associated with spacecraft operations are heterogeneous. As mentioned above, activities include experimental research, spacecraft assembly and checkout, maintenance, repair, and safety monitoring Each of these areas is a domain unto itself, thereby having its own set of methods and heuristics to reason about actions. Hence, it is clear that automated planning systems developed for spacecraft operations must possess a significant amount of domain-independence, and yet allow a modular combination of sophisticated constraints and heuristics in applying specific problem-solving strategies. In addition, with heterogeneous agents performing a heterogeneous set of tasks, a proper balance must be maintained between distributed and global reasoning.

Second, the agents involved in spacecraft operations are also heterogeneous. Each agent possesses a unique combination of physical and functional capabilities, emphasizing distinct skills. Crewmembers, for example, possess differing specialties (e.g., a flight officer, a telerobotic expert, a life-sciences payload specialist) while being similar in physical capabilities and general functionality. On the other hand, on-orbit robots differ greatly in physical capabilities (e.g., Flight Telerobotic Servicer, Special Purpose Dextrous Manipulator, spacecraft assembly cranes, IVA maintenance robots), and by nature address different functional needs.

Third, this environment is naturally dynamic. For example, Space Station Freedom's payload operations will be scheduled into contiguous 90-day increments. Every increment will see new objectives and priorities, while possibly maintaining continuing activities from previous increments. Additionally, there will always be the potential for immediate-term adjustment of priorities to service needs such as emergencies or windows of unexpected opportunity. Such changes in activity schedules call for a strong emphasis on both replanning and monitoring of plan execution. Another dynamic aspect of the domain is evolution. The environment about which the reasoning occurs may evolve as systems are upgraded or reconfigured, thus changing their associated operations tasks. Crew agents will likely evolve as they expand and improve their skill sets through increased space habitation. Robotic agents will similarly evolve as changes in technology produce enhanced capabilities. These continuous changes in agents, their environment, and their activities suggest a requirement for automated planners that are highly flexible and extensible.

## 3. Strategies Addressing Planning Issues

This section discusses aspects of the architecture of on-going investigations at Boeing's Defense and Space Group, Huntsville Division, which address some of the issues highlighted above. Figure 1 depicts an abstraction of the architecture from which this discussion draws. The intent of this research is to provide a foundation which supports multiple aspects of the automated planning problem, including representation, reasoning schemes, and verification.

The issue of heterogeneous agents performing heterogeneous tasks is primarily being addressed with a methodology known as "agent-independent planning" [3]. Agent-independent planning generates activity plans using only the constraints associated with the tasks to be performed and the objects in the environment. Once a plan is generated, an agent is selected for whom the plan is validated, and instructions particular to that agent are translated from the original plan representation (see figure 2). This separation of constraints supports a planning system that is robust in allowing the evolution of tasks independently from the evolution of agents. The primary representation for activity is based on the temporal-interval logic established by James Allen [4]. Networks of temporal intervals form a hierarchically abstracted plan space to describe complex tasks. The system's constraints, which are arranged in a class structure and are similar to the basic planning constraints in SIPE [5], are dynamically grouped as combinations of tasks, objects, and agents are constructed to satisfy particular planning goals. The mechanism for plan generation is a combination of nonlinear and temporal planning techniques. While the very difficult problem of reasoning about multiple interacting agents is not currently addressed by this methodology, it does provide mechanisms to reason about agents with varying skills, and to determine validity among combinations of plans and agents.

The temporal logic employed by the planning system affords a rich scheme for representing activity within the complex domain. However, maintaining logical consistency among the temporal networks is computationally expensive. Of particular difficulty is dealing with the dynamic nature of spacecraft operations, where domain information is sometimes incomplete. This issue is being addressed by developing nonmonotonic capabilities into the temporal logic used by the planner. This provides the ability to retract temporal assertions made by previous inferences without disrupting previous propagations of constraints which remain valid. This capability allows more extensive use of temporal planning techniques, and in particular gives rise to replanning algorithms which also exploit this representation.

For automated planners to be successfully adopted into the potentially-hazardous domain of space, their reasoning methods must be verifiable to ensure safe and consistent operation. This includes not only verifying planner rationale, but also proper execution of the plans by the intelligent agents. Validation of plans during execution is being addressed by using techniques of model-based diagnostics to monitor and detect faults. Just as fault sensors in a physical system can be used to signal failures and characterize symptoms, an agent's sensors provide feedback which can be combined with plan causality structures and models of the environment to determine if and where a plan has failed. Fault detection and isolation algorithms provide a focus for replanning efforts to correct the plan error. Pre-execution plan validation is being addressed by investigating an explanation system which describes the rationale used in generating plans. This rationale is constructed from the plan's causal links, temporal relationships, and models of the domain environment (physical, functional, spatial, etc.). Explanation will be a key factor in integrating human agents with automated planning systems.

## 4. Directions for Research

In addition to the emphasis on intelligent agents, a recent OAST workshop identified both multi-agent reasoning and verification of automated functions as areas needing technology development [6]. While these areas encompass a broad spectrum of technology within automated planning, this section underscores a few that particularly address spacecraft operations issues.

Multi-agent reasoning, in this context, concerns not only the interaction and cooperation of agents but also the mere notion of multiple, heterogeneous agents available for a large variety of tasks. A critical factor to successful reasoning, then, is how well the domain is modeled. Planning for a complex environment requires better representations to deal with the complexity. Current logic and frame representations have afforded continuity in developing planning technology, but tools such as these should be extended to provide more encompassing representations. For example, the temporal interval logic has allowed significant advances in plan reasoning, but must be enhanced to incorporate complex domain issues such as nonmonotonicity. Spacecraft operations should be modeled in a manner that allows reasoning that can determine appropriate amounts of interaction among agents. Such models should address questions of how and when activity can be distributed, where should reasoning be performed, and how accurately must plans be developed.

Rich representational capability is needed to model not only plan behavior, but also the agents and the physical environment. Characteristics of agents should be modeled to facilitate applying agents to meet dynamic needs. The physical and functional models of agents should provide planning constraints not only with agent capabilities, but also with more abstract knowledge such as skill proficiencies, task preferences, and endurance. In terms of cooperating agents, the complex issue of an agent's knowledge or belief of other agents is compounded when certain assumptions can possess hazardous consequences. Representations of the physical environment should follow along the lines of model-based reasoning. Insight into physical component functionality will allow planners to match agent capabilities with object behavior to achieve complex goals.

Verification of automated functions, while difficult, is intensified when applied to the spacecraft operations domain, where there is usually little margin for error. It is critical not only for reliable performance of operations, but also for acceptability of automation among spacecraft personnel. The rationale used in deriving plans must be shown to be satisfactory in order for crewmembers to rely on automated planning. Verification of planning rationale should address multiple levels of resolution, depending on the accuracy desired and time needed to perform the verification. Knowledge-based, model-based, and explanation-based methods are viable emphasis areas for performing and reporting plan validation. Ensuring reliable operation also extends into plan execution and monitoring. Hence, replanning, reactive planning, plan diagnosis, etc. are all valid areas of attention. What will make them useful for spacecraft operations is their integration with complex representations, as described above, to perform more comprehensive reasoning about all aspects of the environment.

## References


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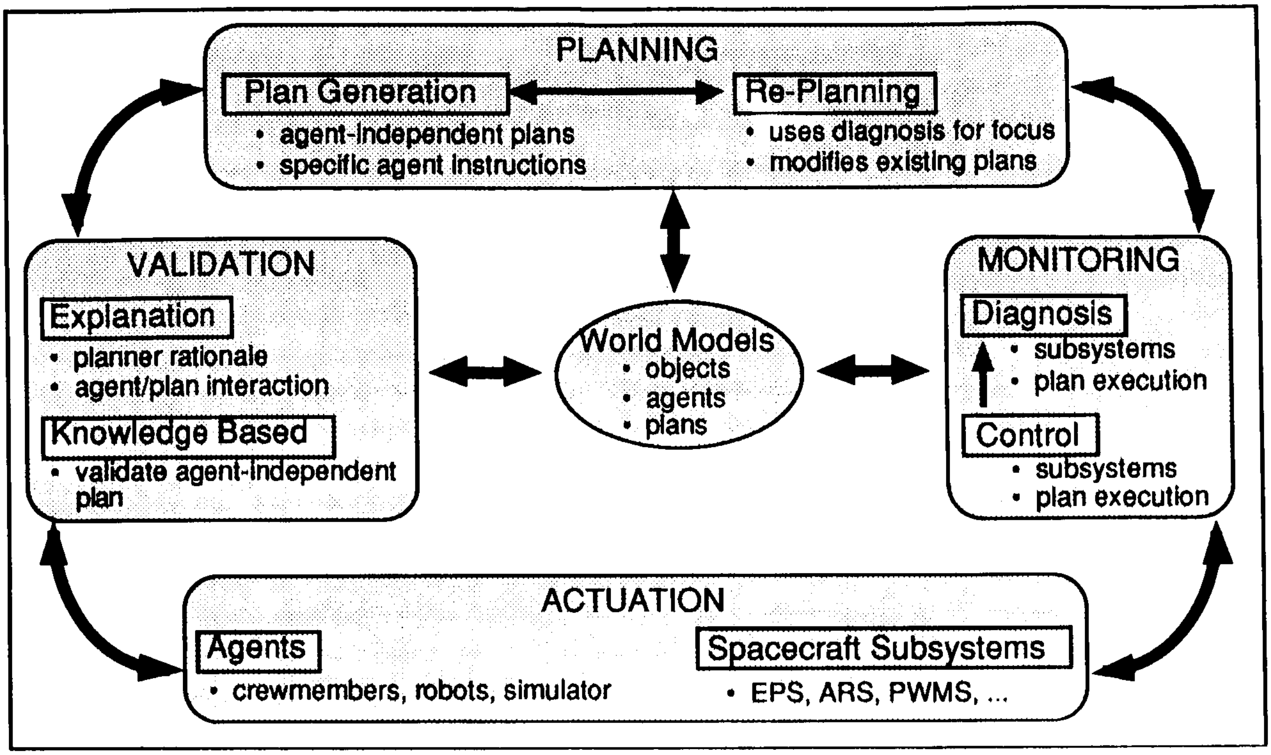


Figure 1: High-level Architecture for Operations Planning

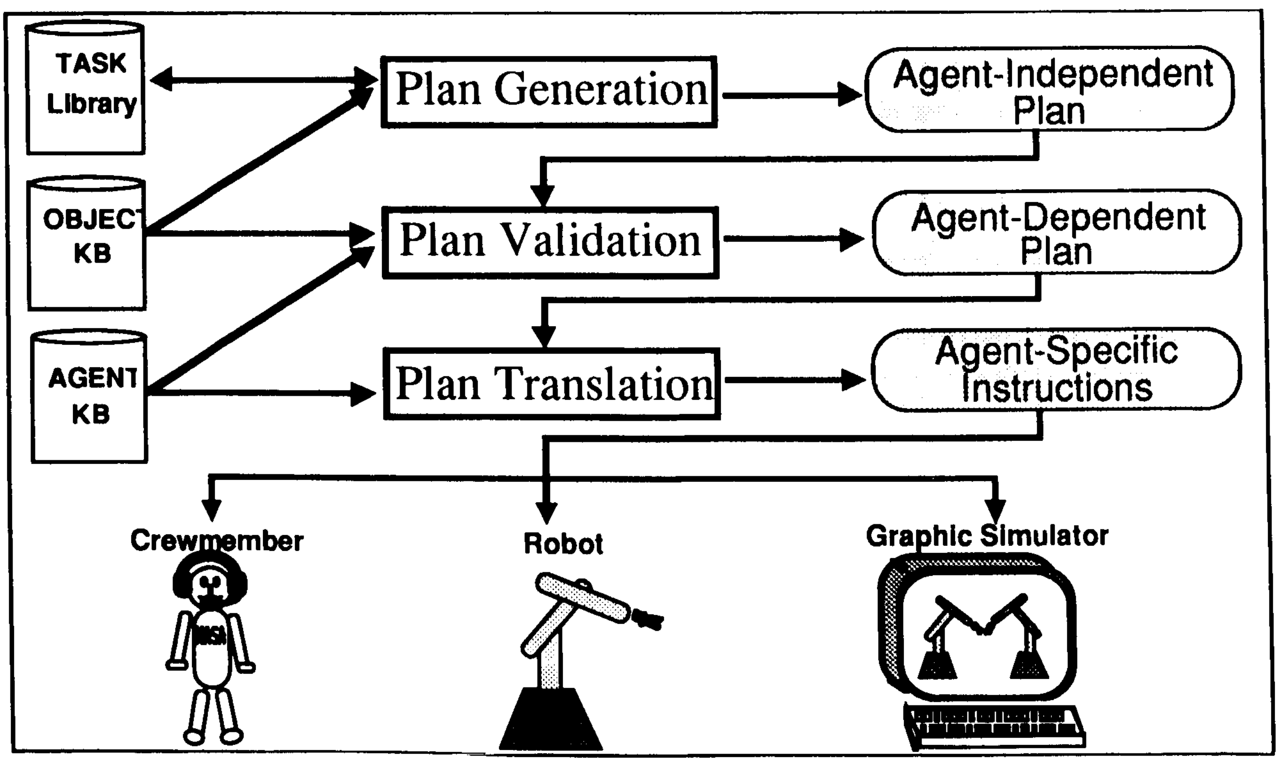


Figure 2: Agent-Independent Planning Process