Planning in Interplanetary Space: Theory and Practice*

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Abstract

On May 17th 1999, NASA activated for the first time an AI-based planner/scheduler running on the flight processor of a spacecraft. This was part of the Remote Agent Experiment (RAX), a demonstration of closed-loop planning and execution, and model-based state inference and failure recovery. This paper describes the RAX Planner/Scheduler (RAX-PS), both in terms of the underlying planning framework and in terms of the fielded planner.

Introduction

During the week of May 17th 1999, the Remote Agent became the first autonomous closed-loop software to control a spacecraft during a mission. This was done as part of a unique technology validation experiment, during which the Remote Agent took control of NASA's New Millennium Deep Space One spacecraft (Muscettola *et al.* 1998; Bernard *et al.* 1999). The experiment successfully demonstrated the applicability of closed-loop planning and execution, and the use of model-based state inference and failure recovery.

As one of the components of the autonomous control system, the on-board Remote Agent Experiment Planner/Scheduler (RAX-PS) drove the high-level goal-oriented commanding of the spacecraft. This involved generating plans that could safely be executed on board the spacecraft to achieve the specified high-level goals. Such plans had to account for on-board activities having different durations, requiring resources, and giving rise to subgoal activities, all while satisfying complex flight safety rules about activity interactions.

In this paper, we describe the Remote Agent Experiment Planner/Scheduler from both the theoretical and the practical perspectives. The architecture of the planning system is as shown in Figure 1. The *domain model* describes the dynamics of the system to which the planner is being applied – in this case, the Deep Space One spacecraft. A *plan request*, consisting of an initial state and a set of goals, initializes the *plan database*. The *search engine* then modifies the plan database to generate a complete valid *plan*, which is then sent to the execution agent. The *heuristics* and *planning experts* are not part of the core framework, but they are an integral part of the planning system that flew on board Deep Space One. The heuristics provide guidance to the search engine while the planning experts provide a uniform interface to external systems, such as attitude control systems, whose inputs the planner has to take into account.

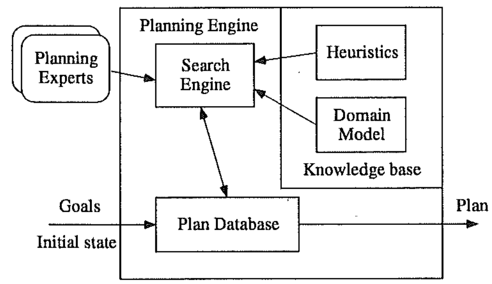

Figure 1: The Planner/Scheduler architecture

Aadditional information about the theoretical and practical aspects of RAX-PS can be found in (Jónsson *et al.* 2000).

Theory

The RAX-PS system is based on a well-defined framework for planning and scheduling that, in many ways, differs significantly from classical STRIPS planning. For instance:

- Actions can occur concurrently and can have different durations.
- Goals can include time and maintenance conditions.

In this section, we will describe the PS framework from a theoretical perspective.

Tokens, Timelines and State Variables

To reason about concurrency and temporal extent, action instances and states are described in terms of temporal intervals that are linked by constraints. This approach has been called constraint-based interval planning (Smith, Frank, & Jónsson 2000), and has been used by various planners, including IxTeT (Ghallab & Laruelle 1994). However, although our approach builds on constraint-based interval planning, there are significant differences. Among those are:

- The use of timelines to model and reason about concurrent activities
- No distinction between actions and fluents
- Greater expressiveness of domain constraints

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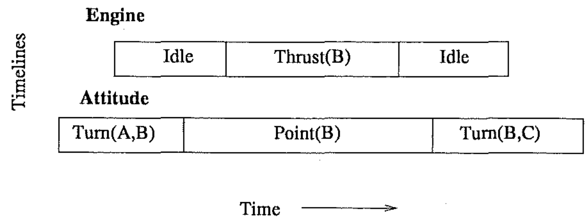

Figure 2: Plans as Parallel Timelines.

Humans find it natural to view the world in terms of interacting objects and their attributes. In planning, we are concerned with attributes whose states change over time. Such attributes are called *state variables.* The history of states for a state variable over a period of time is called a *timeline.* Figure 2 shows `Engine` and `Attitude` state variables, and portions of the associated timelines for a spacecraft application (the attitude of a spacecraft is its orientation in space).

In classical planning (Fikes & Nilsson 1971; McAllester & Rosenblit 1991), and earlier interval planning, there is a dichotomy between fluents and actions. The former specify states, and the latter specify transitions between them. In terms of interval planning, this has resulted in intervals describing only actions, and fluent values being implicit. However, this distinction is not always clear, or even useful. For example, in a spacecraft domain, thrusting in a direction `P` can either be regarded as a state that implies pointing towards `P` or an action with pointing towards `P` as a precondition. Moreover, during execution, the persistence of fluent values over temporal intervals may be actively enforced by maintaining and verifying the value. For these and other reasons, we make no distinction between fluents and actions in this planning approach, and use the same construct to describe both fluents and actions.

From the point of view of execution, a state variable represents a single thread in the execution of a concurrent system. At any given time, each thread can be executing a single *procedure* P. A procedure P has n_P parameters ($n_P \geq 0$), each with a specified type. Each state variable is also typed, i.e., there is a mapping $Procs : \mathcal{S} \rightarrow 2^{\Pi}$, where $\mathcal{S}$ is the set of state variables and Π is the set of all possible procedures. Given a state variable σ, $Procs(\sigma)$ specifies the procedures that can possibly be executed on σ.

Thus, a timeline consists of a sequence of intervals, each of which involves a single procedure. We may think of the interval and its procedure as a structural unit, called a *token*, that has been placed on the timeline. Although each token resides on a definite timeline in the final plan, the appropriate timeline for a token may be undetermined for a while during planning. We refer to a token that is not on a timeline as a *floating* token.

A token describes a procedure invocation, the state variables on which it can occur, the parameter values of the procedure, and the time values defining the interval. To allow the specification of multiple values, e.g, to express a range of possible start times, variables are used to specify parameter, start and end time values for a token. As a result, a token T is a tuple $\langle v, P(\vec{x}_P), s, e\rangle$, where v is a variable denoting a state variable, P is the name of a procedure (satisfying $P \in Procs(v)$), the elements of $\vec{x}_P$ are variables that denote the parameters of the procedure (restricted to their types), and s and e are numeric variables indicating the start and end times respectively (satisfying $s \leq e$).

Each of the token variables, including the parameter variables, has a domain of values assigned to it. The variables may also participate in constraints that specify which value combinations are valid.

Domain Constraints

In a complex system, procedures cannot be invoked arbitrarily. A procedure call might work only after another procedure has completed, or it might need to be executed in parallel with a procedure on a different thread.

To specify such constraints, each ground token, $T = \langle v, P(\vec{x}_P), s, e\rangle$, has a configuration constraint $G_T(v, \vec{x}_P, s, e)$, which we call a *compatibility.* It determines the necessary correlation with other procedure invocations in a legal plan, i.e., which procedures must precede, follow, be co-temporal, etc. Since a given procedure invocation may be supported by different configurations, a compatibility is a disjunction of constraints. Therefore, we define $G_T(v, \vec{x}_P, s, e)$ in terms of pairwise constraints between tokens, organized into a disjunctive normal form:

$$G_T(v, \vec{x}_P, s, e) = \Gamma_1^T \vee \cdots \vee \Gamma_n^T$$

Each Γ_i^T is a conjunction of *subgoals* $\wedge_j \Gamma_{i,j}^T$ with the following form:

$$\Gamma_{i,j}^T = \exists T_j \gamma_{i,j}^T(v, \vec{x}_P, s, e, v_j, \vec{z}_{P_j}, s_j, e_j)$$

where T_j is a token $\langle v_j, P_j(\vec{z}_{P_j}), s_j, e_j\rangle$ and $\gamma_{i,j}^T$ is a constraint on the values of the variables of the two tokens involved.

In general $\gamma_{i,j}^T$ may take any form that appropriately specifies the relation between the two tokens. In practice, $\gamma_{i,j}^T$ is structured to limit its expressiveness and make planning and constraint propagation computationally efficient. In the RAX-PS framework, $\gamma_{i,j}^T$ is limited to conjunctions of:

- Equality (codesignation) constraints between parameter variables of different tokens.
- Simple temporal constraints on the start and end variables. These are specified in terms of metric versions of Allen's temporal algebra relations (Allen 1984); `before`, `after`, `meets`, `met-by`, etc. Each relation gives rise to a bound on the distance between two temporal variables. This bound can be expressed as a function of the start and end variables of T and T_j.
- Constraints on how the token T can be instantiated. These are represented as procedural constraints, which are an effective way to specify and enforce arbitrary constraints.

Subgoal constraints must guarantee that each state variable is always either executing a procedure or instantaneously switching between procedure invocations. This means that each Γ_i^T contains a *predecessor*, i.e., a requirement for a T_j on the same state variable as T, such that T `met_by` T_j. Similarly, each Γ_i^T must specify a *successor*.

The concept of subgoals generalizes the notion of preconditions and effects in classical planning. For example, ADD effects can be enforced by using `meets` subgoals while deleted preconditions correspond to `met_by` subgoals. Preconditions that are not affected by the action can be represented by `contained_by` subgoals.

Plan Database

Having laid out the representation of the planning domain, we can now turn our attention to what the planner represents and reasons about. In RAX-PS, this is a data structure called the *plan database*. At the most basic level, the plan database represents 1) a current *candidate plan*, which is essentially a set of timelines containing interrelated tokens, and 2) a current set of decisions that need to be made.

Formally, a candidate plan consists of the following:

- a horizon (h_s, h_e), which is a pair of temporal values satisfying $-\infty \leq h_s < h_e \leq \infty$
- a timeline $\mathcal{T}_\sigma = (T_{\sigma_1}, \ldots, T_{\sigma_k})$, for each state variable, with tokens $T_i = \langle v, P_{\sigma_i}(\vec{x}), s, e \rangle$, such that each $P_{\sigma_i} \in Procs(\sigma)$
- ordering constraints $\{O_1, \ldots, O_K\}$, enforcing $h_s \leq e(T_{\sigma_1}) \leq s(T_{\sigma_2}) \leq \cdots \leq e(T_{\sigma_{k-1}}) \leq s(T_{\sigma_k}) \leq h_e$ for each timeline $\mathcal{T}_\sigma$
- a set of constraints $\{C_1, C_2, \ldots, C_N\}$, each relating sets of variables from one or more tokens; includes temporal, equality and local procedural constraints

The constraints in a candidate plan give rise to a constraint network, consisting of the variables in the tokens and the constraints that link token variables in different ways. This network determines the set of all legal instantiations of the given tokens. As a result, any candidate plan that has an inconsistent underlying constraint network cannot be part of a valid plan. Limited plan consistency checking can therefore be done by *constraint propagation* (Mackworth & Freuder 1985), which is a method for eliminating values that can be proven not to appear in any solution to the constraint network.

In addition to a candidate plan, the plan database may also contain a set of decisions that need to be made. A decision corresponds to a *flaw* in a candidate plan, an aspect of the candidate that may prevent it from being a complete and valid plan. In this framework, there are four types of flaws: *uninstantiated variables*, *floating tokens*, *open disjunctions of compatibilities*, and *unsatisfied compatibility subgoals.* Each flaw in the plan database gives rise to choices for how that flaw can be resolved. Resolving a flaw is a reasoning step that maps the given database to another database. Categorized by the types of flaws, the following is a list of the possible choices for resolving a flaw:

- Variable restriction flaws are resolved by selecting a non-empty subset of the variable domain and restrict the variable to that domain.
- Floating token flaws are resolved by selecting two adjacent tokens on a timeline and inserting the floating token between them.
- Open disjunction flaws are resolved by selecting one item in the disjunction and making it true.
- Unsatisfied subgoal flaws are resolved by either finding an existing token and using that to satisfy the subgoal, or by adding a new token to satisfy the subgoal.

It is important to note that it is not necessary to resolve all flaws in order to have a plan. In most cases, however, we require that each token satisfy the applicable compatibility specification, i.e, that the subgoals from at least one of the disjunctions are satisfied. In that case, we say that the token is *fully supported.*

Executable Plans

Based on the notions we have introduced here, we can now turn our attention to the semantics of a candidate plan, and the task of developing a formal definition of what a valid plan is. Traditionally, valid plans have been defined in abstract terms, based only on the candidate plan and the domain model. However, this approach is not realistic, as the validity of a plan in the real world is inherently tied to the mechanism that executes it. To address this, we start by discussing the basics of plan execution and then go on to derive a realistic definition of what constitutes a valid plan.

From the point of view of the executing agent (called the executive or EXEC) a plan is a concurrent program that is to be interpreted and executed in a dynamic system. Recall that the plan contains variables that specify how and under which circumstances procedures are to be instantiated. For variables that correspond to system values, such as the current time, the EXEC will sense actual system values, compare them with the values specified in the plan, and then determine which procedure should be executed next. If the EXEC fails to match sensed values with the values in the plan, the EXEC triggers a fault-protection response (e.g., put the system in a safe state and start taking recovery actions). The question of whether the EXEC succeeds in matching values and selecting a procedure invocation depends in part on how much reasoning the EXEC can perform for this purpose. That, in turn, depends both on how much reasoning the EXEC is capable of and how much time it has before the next invocation must be activated.

Consider a candidate plan; tokens may not be fully supported, and variables may be uninstantiated. In order to instantiate the candidate, each flaw must be resolved successfully. For an execution agent with sufficient time and reasoning capabilities, such an underspecified plan might be a viable plan. In fact, the lack of commitment would allow the execution agent to choose the flaw resolutions that best fit the actual conditions during execution. The Remote Agent system took advantage of this by letting the EXEC map high-level tasks into low-level procedures, during execution. This freed the planner from generating low-level procedure calls, and allowed the executive to choose the low-level procedures that best fit the actual execution.

In general, executability depends on the execution agent in question. It depends primarily on two aspects; how flexible the candidate plan must be to cover possible system variations, and how restricted the candidate plan must be for the executive to identify whether it is executable. The latter is an important issue to consider, as making this determination can be as expensive as solving a planning problem.

To represent the abilities of a particular executive agent, we use a *plan identification function* f_I that identifies executable candidate plans, by mapping each possible candidate plan to one of the values of $\{T, F, ?\}$. The intent is that if a candidate $\mathcal{P}$ can be recognized as being executable, then $f_I(\mathcal{P}) = T$; if a candidate is recognized as not being executable, then $f_I(\mathcal{P}) = F$; and if executability cannot be determined, then $f_I(\mathcal{P}) = ?$.

We permit a great deal of variation in how different executives respond to different candidate plans, but we do require that a plan identification function behaves consistently with respect to the two aspects mentioned above. For example, the function should not reject one candidate on the basis of being too restrictive and then accept a restriction of that candidate. This leads us to the following formalization of what constitutes a plan identification function:

Definition 1 *A* plan identification function f_I *for a given execution agent is a function that maps the set of candidate plans to the extended truth value set* $\{T, F, ?\}$, *such that for any candidate plan* $\mathcal{P}$ *and any candidate plan* $\mathcal{Q}$ *that extends the candidate* $\mathcal{P}$, *we have:*

- *if* $f_I(\mathcal{P}) = F$ *then* $f_I(\mathcal{Q}) = F$
- *if* $f_I(\mathcal{P}) = T$, *then* $f_I(\mathcal{Q}) \in \{T, F\}$
- *if a token in* $\mathcal{P}$ *is not supported, then* $f_I(\mathcal{P}) = ?$

The last condition is not strictly necessary, as some executives are capable of solving planning problems, but in the interest of clarity, we will limit the execution agents to solving constraint satisfaction problems.

Using this notion of plan identification functions, we can now provide a realistic, formal definition of what constitutes a plan, namely:

Definition 2 *For a given executive, represented by a plan identification function* f_I, *a candidate plan* $\mathcal{P}$ *is a* plan *if and only if* $f_I(\mathcal{P}) = T$.

Planning process

We can now turn our attention to the plan generation process itself. The input to the planning process is an

```
plan (P,D)  {
   if f(P) = T
     return P
   else if f(P) = F
     return fail
   else
     given a flaw d from the flaw database D,
     choose a resolution res(d) for the flaw
     let (P',D') = apply res(d) to (P,D)
     return plan(P',D')
}
```

Figure 3: The planning process. The plan database consists of the candidate plan P and the set of flaws D.

initial candidate plan, which includes an initialization token for each timeline, a set of floating tokens, and a set of constraints on the tokens in question. Together, these elements give rise to an initial plan database. The goal of the planning process is then to extend the given initial candidate to a complete valid plan. From the point of view of traditional planning, the initial plan database specifies both the initial state and the goals. In fact, our approach permits a much more expressive specification of goals. For example, we can request a spacecraft to take a specified sequences of pictures in parallel with providing a certain level of thrust.

The planning process we define is a framework that can be instantiated with different methods for controlling the search, selecting flaws, propagating constraints, etc. The planning process is a recursive function that non-deterministically selects a resolution for a flaw in the current plan database. An outline of the process is shown in Figure 3.

This planning process is clearly sound, as any resulting plan satisfies the given plan identification function. The planning process is also complete in the sense that if there is a plan, then a plan can be found. Furthermore, if a given initial candidate plan can be extended to some valid plan $\mathcal{P}$ (satisfying f_I), then the planning process can find some other valid plan (satisfying f_I) that can be extended to $\mathcal{P}$. A still stronger completeness criterion, that any given plan can be found, does not hold in general. The reason is that a lenient identification function f_I may return T even though the planning process has not addressed all remaining flaws. This highlights the importance of identifying properties of soundness and completeness for new planning frameworks such as this one.

Theorem 1 *Suppose a domain model, a plan identification function* f_I, *and an initial plan* $\mathcal{P}_0$ *are given. Let* $\mathcal{P}_T$ *be a valid plan (i.e.,* $f_I(\mathcal{P}_T) = T$*) that extends* $\mathcal{P}_0$. *Then, the planning process can generate a valid plan* $\mathcal{P}'$ *that extends* $\mathcal{P}_0$, *and can be extended to* $\mathcal{P}_T$.

Practice

RAX PS extends the theoretical framework into a well-engineered system. The system had to operate under stringent performance and resource requirements. For

Model size:	State variables	18
	Procedure types	42
Plan size:	Tokens	154
	Variables	288
	Constraints	232
Performance:	Search nodes	649
	Search efficiency	64%

Table 1: Plan size and performance of RAX PS

example, the Deep Space 1 flight processor was a 25 MHz radiation-hardened RAD 6000 PowerPC processor with 32 MB memory available for the LISP image of the full Remote Agent. This performance is at least an order of magnitude worse than that of current desktop computing technology. Moreover, only 45% peak use of the CPU was available for RAX, the rest being used for the real-time flight software. The following sections describe the engineering aspects of the RAX PS system. First we describe the planning engine, the workhorse on which all development was founded. Then we describe the mechanism for search control used to fine-tune the planner.

RAX PS planning engine

As follows from the previously discussed theory, producing a planner requires choosing a specific plan identification function f_I, a specific way to implement nondeterminism and a flaw resolution strategy. In RAX PS we designed the planner in two steps. First we defined a basic planning engine, i.e., a general search procedure that would be theoretically complete. Then we designed a method to program the search engine and restrict the amount of search needed to find a solution. In this section we talk about the planning engine.

The first thing we need to clarify is what constitutes a desirable plan for the flight experiment. RAX plans are flexible only in the temporal dimension. More precisely, in a *temporally flexible plan*, all variables must be bound to a single value, except the temporal variables (i.e., token start and end times, s and e). It is easy to see that under these assumptions the only uninstantiated constraint sub-network in the plan is a *simple temporal network* (Dechter, Meiri, & Pearl 1991). This means that the planner can use arc consistency to determine whether the plan can be instantiated and that the executive can adjust the flexible plan to actual execution conditions by using very fast incremental propagation (Tsamardinos, Muscettola, & Morris 1998). All of this is translated into a plan identification function f_I defined as follows: *When applied to a candidate plan, f_I checks its arc consistency. If the candidate is inconsistent, f_I returns F. If the candidate is arc consistent, f_I returns one of two values: T if the candidate is fully supported and all the non-temporal variables are grounded, and ? in any other case.*

To keep a balance between guaranteeing completeness and keeping the implementation as simple as possible, non-determinism was implemented as chronological backtracking. Also, the planner always returned the first plan found. Finally, the planning engine provided a default flaw selection strategy at any choice points of the backtrack search. This guaranteed that no underconstrained temporal variable flaw would ever be selected, while all other flaw selection and resolutions were made randomly.

```
(:subgoal
 (:master-match (Camera = Ready))
 (:slave-match  (Camera = Turning_On))
 (:method-priority ((:method :add)(:sort :asap))
                   ((:method :connect))
                   ((:method :defer)))
 (:priority 50))
```

Figure 4: Search control rules for unsatisfied subgoal

Search control

By itself, the basic planning engine could not generate the plans needed for the flight experiment. However, RAX PS included additional search control mechanisms that allowed very localized backtracking. This is reflected in the the performance figures in Table 1, where search efficiency is measured as the ratio between the minimum number of search nodes needed and the total number explored.

Achieving this kind of performance was not easy and required a significant engineering effort. We outline the principal aspects of this effort in the rest of the section.

Flaw agenda management RAX PS made use of a programmable search controller. Ideally, the "optimal" search controller is an oracle that can select the correct solution choice without backtracking. In practice this is not possible and the control strategy can only make flaw resolution decisions on the basis of the partial plan developed so far. The search controller of RAX PS allows programming an approximate oracle as a list of search control rules. This list provides a prioritization of the flaws in a database and sorting strategies for the non-deterministic choices for each flaw selection. Figure 4 gives an example of a search control rule.

The rule applies to an unsatisfied subgoal flaw of a $\langle \texttt{Camera}, \texttt{Ready}, s, e\rangle$ token that requires a $\langle \texttt{Camera}, \texttt{Turning\_on}, s_k, e_k\rangle$ token. Note that in the DS1 model the `Camera` can reach a `Ready` state only immediately after the procedure `Turning_on` has been executed. Therefore, in this case, matching the token types in the subgoal is sufficient to uniquely identify it. When the priority value associated with the flaw is the minimum in the plan database, the planner will attempt to resolve the flaw by trying the resolution methods in order. In our case the planner will first try to `:add` a new token and try to insert it in the earliest possible timeline gap (using the standard sort method `:asap`). The last resolution method to try is to `:defer` the subgoal. When this happens, the plan database will automatically force start or end of the token to occur outside of the horizon h_s. In our case, the deferment method will only succeed if the `Ready` token is the first token on the timeline.

Search control engineering The rule language for the search controller is designed to be extremely flexible. It permits the introduction of new sorting methods, if the standard methods prove to be ineffective. Also, it is possible to prune both on solution methods (e.g., only `:connect` to satisfy a subgoal) and on resolution alternatives (e.g., schedule a token as early as possible and fail if you cannot). Unfortunately, this meant that completeness could no longer be guaranteed. On the other hand it allowed for a finely tuned planner. Designing search control became a trade-off between scripting the planner's behavior and exploring the benefits of shallow backtracking when necessary. Here are some issues that needed to be addressed.

INTERACTION BETWEEN MODEL AND HEURISTICS: Ideally, it is desirable to keep domain model and search control methods completely separate. This is because constraints that describe the "physics" of the domain should only describe what is possible while search control should help in narrowing down what is desirable from what is possible. Moreover, declarative domain models are usually specified by domain experts (e.g., spacecraft systems engineers) not by problem solving experts (e.g., mission operators). Commingling structural domain information with problem solving methods can significantly complicate inspection and verification of the different modules of a planning system.

In our experience, however, such an ideal separation was difficult to achieve. Model specifications that were logically correct turned out to be very inefficient because they required the discovery of simple properties by extensive search (e.g., a token being the first of a sequence of tokens with the same procedure). The standard method used in RAX-PS was to define auxiliary token variables and use search control to enforce a specific value, which in turn would prune undesired alternatives through constraint propagation. Including the control information within the model caused a significant level of fragility in domain modeling, especially in the initial stages of the project when we still had a weak grasp on how to control the search.

HIGH-LEVEL CONTROL LANGUAGES: The control rules described above can be thought of as an "assembly language" for search control; and the DS1 experience confirmed that programming in a low-level language is painful and error prone. However, this assembly language provides us with a strong foundation on which to build higher level control languages which are well founded and better capture the control knowledge of mission operators. The declarative semantics of the domain model also opens up the possibility of automatically understanding dependencies that point to effective search control. The synthesized strategies can then be compiled into the low-level control rules. Work is currently in progress to explore methods to alleviate the burden of control search programming.

Conclusion

In this paper, we have presented an overview of the Remote Agent Experiment Planning/Scheduling system, both from theoretical and practical points of view. Research and development of autonomous planning systems, capable of solving real problems, continues among the many scientists in the field. The work we have presented here is just another step in this development, but it is a step that has taken autonomous planning to interplanetary space.

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