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Effective search strategy via internal state transition graphs on onboard planning for deep space probes

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ABSTRACT

As to support the mission of Mars exploration in China, automated onboard planning is required to enhance the security and robustness of deep space probes. Onboard planning here is a term that defines a complex set of activities or states aiming at deciding the daily tasks on a probe and at figuring out if mission goals are met. Deep space onboard planning requires modeling of complex operation constraints and focusing on intricate state transitions of involved subsystems. Also, devices of various operation modes and multiple functionalities, which are ubiquitous in physical systems, are intractable in onboard planning and have not been effectively handled. To cope with these difficulties, we introduce an approach of knowledge representation that explicitly establishes the mentioned features. The key techniques we build on are the notion of timeline-based planning tasks and heuristic estimate method designed on internal state transition graphs. Furthermore, state transitions have provided crucial information for search guidance, and a search algorithm joint with internal state transition graph heuristic method is proposed to avoid redundant work. Finally, we run comprehensive experiments on selected domains, and our techniques present an excellent performance compared to the algorithm in Europa2.

1. Introduction

Automated onboard planning technology, to support CNSA's Mars exploration mission in 2020, offers considerable promise in automating deep space operations [1–4]. On the basis of perception and cognition of the space environment, autonomous planning for operations of deep space probes involves generating a sequence of low-level commands from a set of high level science and engineering goals, which are uploaded from the ground. It will reduce mission operations costs by taking over many of the operations that have typically been conducted on the ground, and will improve mission quality by being more robust to failures than traditional spacecraft [5,6].

Due to the complex nature of observation and space environment uncertainties, it is difficult to directly map the approaches from classical planning systems to deep space probe systems [7–9]. Moreover, complex and dynamic contexts may attenuate or impede the path to goal attainment when probes are confronted with the challenge of long-duration space missions [10,11]. Since various operation modes and alternative functionalities of onboard devices become more prevalent, traditional methods are no longer affordable on well describing and organizing these complex features. In view of the vast potential for automated planning to improve deep space missions, it becomes one of the key technologies seeking a suitable approach for deep space onboard planning.

In recent decades, the technologies for the spacecraft states description have been diversified and advanced rapidly [12,13]. As the challenges of space missions have grown over time, the standard approach to describe the probe falls apart due to growing complexity of physical systems [14,15]. Deep space probes require more concise descriptions of problem domains, and behaviors of involved subsystems are supposed to be described as temporal functions. Furthermore, backup devices used in exceptional conditions bring challenges to knowledge description while guaranteeing the security of probes. And the diversity of system functions may provide multiple ways to achieve mission objectives. For example, a camera B can be employed for current tasks when failures occur on camera A. Since multi-functional devices provide alternative choice for planner, which may impact local search techniques, it is more expected to adopt an effective search guidance for a better performance.

Automated planning techniques play an important role in many aspects of deep space explorations. For example, assembly planning creates the exploded views for the visualization purpose and the

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verification of assembly plans, and is crucial to the success of complex systems such as spacecraft [16–18]. And in this research, we focus on approaches that decide appropriate sets of activities or states to arrange the daily tasks of space probes. The Rosetta mission, which is the first rendezvous with and landing on a comet, conducts science planning by a Master Science Plan (MSP) and develop an observation plan that adequately addresses the mission's science objectives while coping with dynamic contexts [1]. Due to a largely unknown and continuously evolving environment, Rosetta focuses on more flexible strategies to enhance the security of spacecraft. And there may not be much research on search techniques involved in shifted states of onboard devices. A well-known planning system—the Advanced Planning and Scheduling Initiative (APSI) framework [19,20], which has been deployed for Mars Express, copes well with constraint reasoning on resource and temporal relations. But it may not devote much effort to the features of state transitions. The Extensible Universal Remote Operations Planning Architecture (Europa) [21], which was designed to determine a plan that enables goal-based spacecraft commanding, has been flight validated during an experiment onboard NASA's Deep Space 1. The Europa planning system, where activities and states of each subsystem are modeled in a unified form, has demonstrated to be successful owing to the notion of timelines [22,23]. Europa is now at version 2 and is the successor of the original Europa, and we use Europa2 for comparison in our simulation tests. Nevertheless, as there is not much research on search guidance, it may have an impact on efficiency and reliability of plans during execution. More generally, automated planning techniques tend to be more reasonable and more comprehensive [24,25], but problems still remain due to highly complex functions of physical systems. Thus, in this research, we devote our effort on knowledge representation and effective search strategies for a better performance on deep space onboard planning.

The paper is structured as follows. Section 2 provides basic concepts and necessary definitions for state timeline knowledge. In Section 3, we present the concept of timeline-based planning tasks and internal state transition graphs. We then describe the core module—state transition graph heuristic strategy and Internal State Transition Graphs based Planning (ISTGP) algorithm in Section 4 and run comprehensive experiments in Section 5 to verify the validity of our heuristic planning algorithm. And finally, the conclusion is provided in Section 6.

2. State timeline representation for deep space probes

Deep space probes require modeling of evolving behaviors of subsystems over a temporal horizon. Thus, we utilize the notion of state timelines, which has been stated in Ref. [26] as the conceptual repositories for state knowledge, to denote the behavior of the deep space probe in the planning problem. In this Section, we provide the basic knowledge compilation method of the planning model.

In order to explain our methods, it is necessary to have some understanding of state timeline knowledge, and we give a quick overview of the essentials in this section.

Definition 1. State variables

A state variable is an abstraction of system knowledge for a deep space probe, which can be defined as a 4-tuple:

$$SV = < N, U, T, D> \tag{1}$$

where N is the name of the state variable; U is a non-empty set of the state variable values (i.e. states); T denotes value transition rules of the state variable; D is called the duration function. For example, a propulsion subsystem is described as a state variable in the model of a deep space probe, which is depicted in Fig. 1.

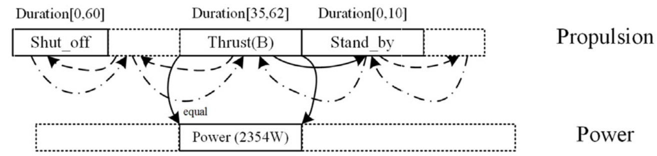

Fig. 1. Illustration of the state variable of a propulsion subsystem.

Definition 2. States

A state[1] is the value of a state variable at a time point or during a temporal interval, which is represented as a 3-tuple:

$$S = < N_s, U_s, D_s> \tag{2}$$

where N is the name of the state; U_s is the set of parameters; D_s is the duration function of the state. And it is worth noting that aiming at coping with uncertainty during actual execution, the duration function is defined in the form of intervals, namely $D_s \in [d, d']$.

Definition 3. State timelines

A state timeline represents the evolving behavior of a state variable over the planning horizon.

If SV is a state variable, a state timeline is a finite sequence of states for SV without gaps over the given horizon, whose identifiers are $s_0, s_1, ..., s_{n-1}, s_n$:

$$STL = (s_0, s_1, ..., s_{n-1}, s_n) \tag{3}$$

Consider the propulsion subsystem, for example, a timeline is a sequence of “Shut_off”, “Stand_by”, “Thrust” and other states over a certain time interval. If the horizon is determined for one day, so we have to manage the relevant sequence of states to fill the entire state timeline for the given day. As shown in Fig. 1, a state timeline consists of a sequence of non-overlapping states, and the length of the whole sequence represents the temporal interval, i.e., the planning horizon. Essentially, there are no gaps between two adjacent states. And a feasible solution to the planning problem, which contains a complex set of daily tasks on a spacecraft, is a set of state timelines.

Definition 4. Solution plans

A solution plan π is a set of state timelines over a given horizon:

$$\pi = (STL_0, STL_1, ..., STL_{k-1}, STL_k) \tag{4}$$

where $STL_0, STL_1, ..., STL_{k-1}$ and STL_k denote a set of state timelines, which satisfies the planning goal and the deep space probe operation rules.

3. Timeline-based planning tasks

3.1. Representation of timeline-based planning tasks

Automated planning technology can reduce mission operation costs by taking over many of the operations that have typically been conducted on the ground, and will improve mission quality by being more robust to failures than traditional spacecraft. Knowledge description for the spacecraft is the basis of onboard planning, and appropriate modeling methods may improve the efficiency of planning. In addition, as the challenges of space missions have grown over time, the standard approach to describe space probes falls apart due to growing complexity of systems. Consider the multiple subsystems and complex operation constraints of deep space probes. It has turned out that onboard planning for deep space probes may benefit from a more concise and declarative knowledge description. In addition, various operation modes and functionalities of onboard devices lead to multiple possible

[1] The concept of the state here is not exactly the same as the concept of world state in classical planning. Without loss of generality, we use “world state” to represent the latter one.