Acta Astronautica 151 (2018) 779–790

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Re-planning strategies for space station on-orbit activities executed in emergencies

Shuai Mu[a], Ya-zhong Luo[b,*], Dong-yang Qiu[b], Jun Liang[b]

[a] Hypervelocity Aerodynamics Institute, China Aerodynamics Research and Development Center, Mianyang, China
[b] College of Aerospace Science and Engineering, National University of Defense Technology, Changsha, China

ARTICLE INFO

Keywords:
Space station
Mission re-planning
Heuristic
Emergency

ABSTRACT

In this paper, we develop strategies for the problem of space station on-orbit activity re-planning. Considering the effects of emergencies, a preprocessed strategy is firstly proposed to reconstruct conflicting missions. Furthermore, a greedy algorithm with interval-based strategies is used to re-plan the activities of the reconstructed missions by utilizing mission priority and preplanned activity schedule intervals. Taking into account the propagation of complicated constraints, a time backtrack iteration strategy is adopted to solve constraint conflicts. We demonstrate the proposed approach with a notional operation scenario of the Chinese future space station. The results indicate that our method can successfully re-plan space station on-orbit activities when emergencies occur, all constraint conflicts can be solved, and mission accomplishment rate is increased, in comparison with a method that does not include re-planning strategies.

1. Introduction

Several space stations, such as the International Space Station (ISS) [1,2], have been successfully built and operated, and various space missions have been carried out on these stations [3]. Generally, space station on-orbit activities are accomplished by means of a preplanned schedule [4]. However, the platform conditions are not always stable, as unexpected events such as astronautic mis-operations, equipment failure, and sudden environmental changes may affect preplanned mission execution [5–7], there are also some unexpected risks influencing human health and performance [8]. Therefore, an effective, real-time re-planning method is very important for operating space station efficient. Moreover, as an important component of space station operations, real-time re-planning of on-orbit activities has been successfully applied to certain practical missions. For example, ASPEN [9], which is automation planning and scheduling software, has been used in the ISS. McCormick [10] summarized the ISS execution re-planning process. A consolidated planning system has been increasingly developed in international planning software, to continually meet the most immediate user needs [11]. An onboard autonomous mission re-planning system for Multi-Satellites System has been presented [12]. Real-time re-planning also forms a basic aspect of a robotics planning system [13]. Although various planning or re-planning systems have been put into practice, the planning models, methods, and strategies involved are seldom known to the public.

With the development of space exploration, the problem of space station operation has been studied extensively in recent years, particularly in China, which intends to operate its own space station by 2020 [14,15]. From the perspective of operational time intervals, Luo et al. [16] divided space station operation into four levels: long-term, middle-term, short-term, and detailed. Furthermore, Lin et al. [17,18] proposed a logistics strategy for long-duration space station operations, in which a physical programming method is employed to optimize operational scenario parameters. Bu et al. [19–21] developed an ontology modeling-based planning method for short-term space station mission planning. However, the aforementioned space station operation studies were limited to nominal mission planning, in which the effects of emergencies were not considered. To the best of the authors' knowledge, no efficient method exists for solving the on-orbit activity re-planning problem for space station operation.

In order to develop an effective re-planning method for on-orbit space station activities, it is worth considering a number of re-planning methods used in other fields. Taking into account probable technical failure in satellite operations, Garber and Pate-Cornell [22] presented a model that attempts to quantify risk, performance, and cost tradeoffs. In order to analyze the uncertainty of the Remote Exploration and Experimentation system, Mishra et al. [23] investigated a technique for computing uncertainty in output metrics of stochastic models, due to

* Corresponding author.
E-mail addresses: m15116492416@163.com (S. Mu), luoyz@nudt.edu.cn (Y.-z. Luo), gfkdqiu@163.com (D.-y. Qiu), lj2820329762@sina.com (J. Liang).

https://doi.org/10.1016/j.actaastro.2018.07.030
Received 8 June 2017; Received in revised form 21 June 2018; Accepted 14 July 2018
Available online 17 July 2018
0094-5765/

epistemic uncertainties in the model input parameters. Joppin and Hastings [24] developed a model of a serviceable scientific mission to study on-orbit repair and upgrading, and in light of the Hubble Space Telescope example, upgrading can significantly increase mission utility. Arneson and Bloem [25] presented an approach to scheduling ground delay and airborne holding, for flights that are scheduled to fly through airspace with uncertain capacity constraints. Although these methods are useful, they cannot be directly applied to a space station.

To address the problem of space station on-orbit activity re-planning, in this study, a new sequence of activities is generated based on the preplanned schedule when certain emergencies occur during operation. The goal of this study is to propose a planning approach that can be able to reconstruct space station on-orbit activities by considering emergencies, to re-plan the reconstructed activities in real time, and to obtain an updated activity schedule satisfying all constraints. The remainder of the paper is organized as follows. Section 2 describes the re-planning problem. Section 3 describes the re-planning model, considering mission, activity, resources, and constraints using the ontology theory [21,26]. A preprocessing strategy and greedy algorithm with types of resolving strategies for re-planning activities are proposed in section 4 [27]. A notional 24-h space station operation scenario, involving 16 missions, 43 activities, 29 kinds of resources, and three unexpected missions, is used to testify the re-planning method in section 5. Finally, the major conclusions are summarized in section 6.

2. Space station on-orbit activity Re-planning problem

In order to describe the problem more clearly, some specific meanings of the terms are given first. The definitions are shown in Table 1.

Space station operation efficiency is considerably dependent on activity planning and re-planning quality. From the perspective of operational time intervals, space-station mission planning can be divided into four types: long-term, middle-term, short-term, and detailed planning [16,28]. Space station on-orbit activity re-planning is part of detailed planning, and its optional time interval is selected as one day. Every day, various missions are executed on the space station by following a preplanned schedule, such as orbit maintenance, earth observation, and scientific tests. Furthermore, every mission includes a series of consecutive activities. However, the space station's state is not always stable, because some unexpected events, such as instrument damage, incorrect operating, and urgent avoidance, may occur at any time and even interrupt the execution of preplanned activities. As a result, certain constraint conflicts may generate between these unexpected events and preplanned activities, and they will affect the entire operation significantly. Thus, an effective real-time re-planning method is very important for space station operation.

Space station on-orbit activity re-planning constitutes a dynamic constraint satisfaction problem, the essence of which is to determine the start time of the re-planned missions and enable activities to satisfy all schedule constraints. Re-planning is carried out on the preplanned schedule when an unexpected event occurs during the on-orbit activity operation. Due to the multiple platform constraints, if an execution must be suspended, this causes unfinished missions to be canceled or delayed. In order to reduce the emergency's impact, missions with a higher priority should be executed as early as possible and most preplanned activities should be carried out. Therefore, the objective of space station on-orbit activity re-planning is to re-plan the unfinished mission activities and update the activity schedule in real time. The detailed re-planning process is shown in Fig. 1.

In order to obtain an updated activity schedule, various critical issues should be solved during the re-planning process. The first is to reconstruct the missions affected by the unexpected events. For example, certain types can be executed sequentially on the basis of accomplishment, such as observation, sleeping, and entertainment, so the parameters like the earliest starting time, the duration of this missions would be changed. Others, however, must be re-executed from the start time, such as maintenance and physics experiments. Furthermore, certain activities may be canceled if they are interrupted, such as chemical and biological experiments. The second issue is to arrange the reconstructed missions and reduce the impact of emergencies, which means that multiple objectives should be considered, such as the preplanned schedule's stability, mission accomplishment rate, and total priority of the updated schedule. The final problem is to solve the multiple constraints when certain activities are postponed or shifted, such as the activity execution sequence of a mission, resource capacity, and platform constraints.

Table 1
Definitions of the terms.

Terms	Definitions
Mission	The tasks need to be done on the space station.
Activity	The specific operational steps of a mission.
Resource	The specific things used for activities, such as electricity power, communication bandwidth and so on.
Unexpected event	Some events that cannot be predicted in advance during the space station operation, such as instrument damage, incorrect operating and so on.
Emergency	The urgent tasks which need to be prioritized in the unexpected events.
Unexpected mission	The specific representations of emergency, and provided by emergency assessment system.

3. Re-planning model

3.1. Domain ontology model

Bu et al. [21] noted that the domain ontology model is a reasonable method for describing the space station mission planning problem, including aspects of the mission, activities, resources, and relationships. Based on that study [21], a space station re-planning model is formulated, in which mission priority is defined and mission execution properties proposed.

A mission is an event consisting of a series of activities, which utilizes the space station resources to complete work in a certain manner and satisfy the space station operation requirements. In this study, a mission is defined using nine elements, as follows:

$$M = \{I_{\mathrm{M.\,I.}}, N_{\mathrm{M.\,M.}}, t_{\mathrm{M.\,E.\,S.}}, t_{\mathrm{M.\,L.\,E.}}, E_{\mathrm{M.\,P.}}, O_{\mathrm{M.\,O.\,I.}}, S_{\mathrm{M.\,C.}}, S_{\mathrm{M.\,E.\,T.}}, A\}, \tag{1}$$

where M is the mission; $I_{\mathrm{M.\,I.}}$ is its unique ID to distinguish it from other missions; $N_{\mathrm{M.\,M.}}$ denotes its meaning; $t_{\mathrm{M.\,E.\,S.}}$ denotes the earliest time for starting this mission; $t_{\mathrm{M.\,L.\,E.}}$ denotes the latest time for ending this mission; the interval between $t_{\mathrm{M.\,E.\,S.}}$ and $t_{\mathrm{M.\,L.\,E.}}$ is the optional interval for executing the mission; $E_{\mathrm{M.\,P.}}$ is a number for expressing its priority; $O_{\mathrm{M.O.\,I.}}$ is used to describe its other information, such as function, special requirements, and effects; $S_{\mathrm{M.\,C.}}$ defines its class; $S_{\mathrm{M.\,E.\,T.}}$ defines its execution type; and A is the set of activities that belong to it. The priority indicates the degree of urgency of the mission, with the lowest priority being 0 and the highest 100, as expressed in Eq. (2):

$$E_{\mathrm{M.\,P.}} \in [0,100]. \tag{2}$$

The mission types include ν_{Cr}, ν_{Em}, ν_{Cr}, ν_{Pa}, and ν_{Un}, as expressed in Eq. (3):

$$S_{\mathrm{M.\,C.}} \in \{\nu_{\mathrm{Cr}}, \nu_{\mathrm{Em}}, \nu_{\mathrm{Da}}, \nu_{\mathrm{Pa}}, \nu_{\mathrm{Un}}\}, \tag{3}$$

where ν_{Cr} indicates that the mission is paroxysmal and urgent, ν_{Em} means the mission is very important, ν_{Cr} means the mission is common for maintaining the space station, ν_{Pa} means its execution is for payload experiments, and ν_{Un} means the mission type is undefined. The mission execution property types include ν_{No}, ν_{Al}, and ν_{Re}, as expressed in Eq. (4):