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Space station overall mission planning using decomposition approach ☆

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ABSTRACT

During a space station operation scenario, there are complicated interaction relationships and restrictions between different types of operation missions, including on-orbit experiment arrangements, crew rotation, selection of flying orbit, and the cargo vehicle resupplying strategies. The space station overall mission planning, considering all the operation missions concurrently and comprising the launch window constraints of visiting vehicles, is focused on obtaining appropriate operation arrangements, improving program utilisation capability, and minimising lifecycle operation cost. A hierarchical, three-level, decomposed framework is proposed to model the overall mission planning problem, in which the first-level problem deals with the top-level mission scenario parameters, the second-level problem deals with the vehicle visiting strategy, and the third-level problem deals with the flying orbital missions. In accordance with the hierarchical problem framework, the planning approaches for each level problem are analysed and developed. Furthermore, the integrated planning procedure for the overall planning problem is formulated. The results prove that planning different operation missions concurrently is helpful in satisfying the complicated constraints, thus improving program benefit and decreasing operation cost, and it is essential and more practical to consider launch window constraints in the planning model.
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1. Introduction

The United States of America, Russia, and other countries have successfully built and operated several space stations such as the International Space Station (ISS) and Mir. A space station, designed to orbit for years or decades, operates continuously with various operation missions occurring simultaneously for long periods of time, including onboard crew activity and rotation, onboard experiments, system maintenance and goods supply, rendezvous and docking to visiting vehicles. In fact, there are certain interaction relationships and restrictions between these operation missions, thus they should be planned as a whole. The space station overall mission planning in this study is defined to concurrently plan multiple operation missions within an integrated space station long-duration operation scenario. It is with respect to the program utilisation benefit and operation cost, beginning at the space station conceptual design phase and helpful for the program designers.

The space station mission planning is executed before or during an operation scenario. It is helpful in arranging operational missions, allocating resources to satisfy the required operational constraints, and ensuring the normality and safety of the space station's long-duration operation [17]. Since space stations have a long operational time, their operation mission management and the corresponding mission planning are executed as a multi-level framework. For instance, the ISS mission planning is being performed in several distinct steps—strategic planning, tactical planning, pre-increment planning, and increment execution—with different planning steps focused on the different space station operation phases [9]. De Matteis et al. [3] investigated the Strategic and Tactical Planning support Tool (STPT) for the ISS strategic and tactical planning, which begin about 5 years and 30 months before one increment respectively. To some extent, the space station overall mission planning is similar to the strategic and tactical planning. It is mainly performed to concurrently achieve top-level planning for on-orbit utilisation arrangements, crew rotation and manned vehicle visiting schedule, flying orbit selection and orbital manoeuvre strategy, as well as the cargo vehicle resupplying scheme, during a long-duration operation scenario [10]. China intends to operate its own space station by 2020 [25]. Thus, an in-depth understanding of the space station overall mission planning for long-duration operation scenarios is very significant.

Many investigations have been conducted in space station mission planning. Schwaab [19] developed the Automated Logistics Element Planning System (ALEPS) for Space Station Freedom Program to obtain an optimal solution to the flight load plan for a given increment manifest. Focusing on minimising crew time requirements and maximising efficiency, Ney and Looper [14] studied the integrated planning for logistics and maintenance executed by pressurised operations, extravehicular activity and extravehicular

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robotic activity, for the ISS Program and the Exploration Program. Lin et al. [11] established a dynamic programming modelling approach for the design of space station flying orbit and the orbital manoeuvre strategy. Ho et al. [5,6] studied a concurrent optimisation formulation for the design of space station habitat and its logistics system, concerning the mass-to-orbit, launch frequency, crew number and expected maintenance time. Penley et al. [15] introduced the research disciplines of the ISS challenged by its international nature and multi-level planning framework. Jules [7] discussed the science planning, execution and research accomplishment on the ISS. Russell et al. [18] analysed the crew-time allocation on the ISS and indicated that the mission designers should pay more attention to the habitat maintenance.

Previous studies have limitations in that they mainly concentrate on one single aspect of space station mission planning, such as the planning of flight load, maintenance mission, orbital mission, logistics system, onboard research arrangement or crew rotation [5–7,11,14,15,18,19]. In fact, the interaction relationships and restrictions between multiple operation missions should be planned concurrently to improve the program benefit and decrease the operation cost from the point view of an integrated scenario. In addition, the visit times of manned and cargo vehicles are normally the primary content of space station mission planning in practice, which are constrained to satisfy the crew rotation period, deadline for resupply and especially the rendezvous launch window. Nevertheless, the launch window constraints of visiting vehicles were not considered in the previous planning model [5–7,11,14,15,18, 19].

In this paper, the authors propose a novel planning concept, namely the space station overall mission planning, wherein multiple operation missions are planned concurrently within an integrated long-duration operation scenario. It helps to satisfy the complex constraints caused by the interaction effects and is significant for the design of space station programs. Nevertheless, it is characterised as an extremely complicated planning problem. Based on the characteristics of long duration, multi-objectives, and multi-constraints, a decomposition approach is employed to model the overall mission planning problem as a three-level problem of mission scenario planning, vehicle visiting planning, and orbit mission planning. According to the hierarchical models, the integrated planning procedure is formulated to integrate the multi-level planning framework. Moreover, launch window constraints of visiting vehicles are introduced into the space station overall mission planning model. The rendezvous launch window is planned by considering the constraints of the angle between the Sun and orbital plane, coplanar requirement and initial phase angle between the target's and chaser's orbits.

The space station overall mission planning is applied to a notional one-year operational scenario of China's future space station. The results indicate that the proposed decomposition approach is capable of obtaining the appropriate solutions that satisfying the complex constraints caused by the interaction relationships and restrictions between multiple operation missions. This study can be of practical relevance for mission planning of China's future space station.

2. Description and definition of planning problem

2.1. Space station overall operation missions

In a space station operation scenario, there are two categories of operation missions: on-orbit operations and logistic operations, as shown in Fig. 1. On-orbit operations are executed onboard the station, including repair and replacement of systems, experiments and utilisation, orbital manoeuvres, and crew activities, all of which lead to resource consumption. Since on-orbit resources are limited and the astronauts' physiological and psychological health must be given due consideration, regular traffic to the space station is required for cargo resupply and crew rotation. Logistics operations are mainly planned and executed on Earth and support on-orbit operations by resupplying resources and rotating crew through the use of cargo and manned vehicles. Manned vehicles are also used to rescue the crew for emergency situations.

Mutual interaction relationships exist between the different kinds of operations as seen in Fig. 1, where the solid arrows represent the inducing relationships and the dashed arrows show the restrictive relationships between two operation missions. (1) The flying orbit selection and orbital manoeuvres must take into consideration the experiment requirements, payload carrying capability of cargo vehicle, propellant for compensating orbital decay, rendezvous compatibility, and radiation environment for crew health. For example, performing microgravity experiments requires a continual period lasting more than 30 days during which no orbital manoeuvre is allowed [13,15]. (2) The visiting interval of two successive manned vehicles should not be longer than the crew rotation period for the sake of crew health restrictions. (3) The minimum inventory quantity of each category of resources stored onboard the station, including crew provisions, maintenance spares, propellant, and utilisation materials and instruments, are set to ensure and even enhance the station's on-orbit operational security. When any one category resource's stored mass is close to its minimum value, it is time for a cargo vehicle to resupply resources to the station. (4) The total quantity of the resupply resources should not exceed the maximum payload carrying capacity of the cargo vehicle.

2.2. Space station overall mission planning

The space station overall mission planning, taking into account multiple operation missions concurrently, is mainly performed to obtain the appropriate and optimal operation arrangements within an operation scenario, and it is aimed at providing an analysis of and an evaluation assistance for the conceptual design of the space station program. It will provide top-level planning for all the on-orbit and logistic operation missions such as crew activities and rotation, flying orbit selection and orbital manoeuvres, maintenance of systems, and cargo vehicle resupply schedule, taking into account the complicated inducing and restrictive relationships between them.

2.2.1. Objective functions

The expected products of overall mission planning are the performance indexes of both utilisation benefit and operation cost, which will be explained in detail below.

The utilisation benefit of a space station program results primarily from healthy and qualified engineers and scientists (namely, the crew) being able to spend a certain amount of time onboard the station. First, the research benefit should scale linearly with both the number of people (crew size) and the duration of their stay. Therefore, the first objective function is the total crew on-orbit days

$$\max f_1(\mathbf{X}) = T_{cr} = \sum_{i=1}^{N_{cr}} d_{cr}(i) \tag{1}$$

where T_{cr} is the total crew on-orbit days, N_{cr} is the size of the crew onboard, and $d_{cr}(i)$ is the onboard duration of the ith crew.

In order to achieve productive research, however, the crew needs to have specific utilisation equipment and scientific instruments, such as cameras and spectrometers. Hence, the second objective function is the total upload utilisation mass

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