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Space station orbit design using dynamic programming ☆

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ABSTRACT

A space station orbit design mission is characterized by a long-duration and multi-step decision process. First, the long-duration design process is divided into multiple planning periods, each of which consists of five basic flight segments. Second, each planning period is modeled as a multi-step decision process, and the orbital altitude strategies of different flight segments have interaction effects on each other. Third, a dynamic programming method is used to optimize the total propellant consumption of a planning period while considering interaction effects. The step cost of each decision segment is the propellant for orbital-decay maintenance or lifting altitude, and is calculated by approximate analytical equations and combining a shooting iteration method. The proposed approach is demonstrated for a typical orbit design problem of a space station. The results show that the proposed approach can effectively optimize the design of altitude strategies, and can save considerable propellant consumption for the space station than previous public studies.

1. Introduction

Currently, USA, Russia, etc. have successfully built and operated several space stations, such as the International Space Station (ISS) and the Mir space station. A space station, designed to run in space for years or decades, operates continuously with various operation missions for long periods of time. These operation missions include onboard crew rotations, onboard experiments, flight orbit adjustment, and docking with resupply spacecraft. Space station mission planning, which is executed before or during an operation scenario, focuses on obtaining appropriate operation arrangements, improving station utilization capabilities, and minimizing lifecycle operation cost [1].

Within the space station mission planning, the orbital design plays an important role [2] and has been the topic of many investigations. The relationships between the orbital behaviors and the ground coverage, Earth observation and onboard experiments should be taken into account during this design process [3]. Among all six orbital elements, the orbital inclination and the orbital altitude (or the semi-major axis) are the major design variables. The selection of the orbital inclination mainly considers the requirements of Earth-related experiments and the latitudes of major launch sites. The selection of the orbital altitude needs to consider many factors, such as requirements of microgravity experiments, altitude decay, capacity of resupply vehicles, and the compatibility with the launch and docking of resupply vehicles [4].

The orbital inclination of a space station is usually fixed during the operational phase once it has been determined during the design phase [2]. In contrast, the operational altitude of a space station varies as time changes. The operational altitude is constrained by two aspects: the capabilities of resupply vehicles and the altitude-decay effect of the residual atmosphere [5]. The two categories of constraints were used by Messerchmid and Bertrand [2] to determine the orbital altitude of ISS: to prepare an upcoming docking mission, the altitude of the ISS would be kept as low as possible to maximize the payload mass delivered by resupply vehicles; after this docking mission,

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Nomenclature

h	initial altitude of each flight segment
Δv	impulse of orbital maneuver during each flight segment
t	time of orbital maneuver during each flight segment
Δm	propellant consumption of orbital maneuver during each flight segment
$\upsilon_1(x_1, u_1)$	step cost of the first decision segment, i.e. propellant for altitude lifting during the first altitude-lifting segment
$\upsilon_2(x_2, u_2)$	step cost of the second decision segment, i.e. propellant for orbit maintenance during the autonomous flight segment
$\upsilon_3(x_3, u_3)$	step cost of the third decision segment, i.e. sum propellant for altitude lifting during both the rendezvous and docking and the second altitude-lifting segment
$\upsilon_4(x_4, u_4)$	step cost of the fourth decision segment, i.e. propellant for orbit maintenance during the complex flight segment
δa_n	semi-major axis deviation

Subscripts

Lift_1	first altitude-lifting segment
Auto	autonomous flight segment
RVD	rendezvous and docking (RVD) segment
Lift_2	second altitude-lifting segment
Complex	complex flight segment
f	final

the orbit of the ISS would be lifted to the maximum operational altitude in order to reduce the altitude-decay effect of the residual atmosphere. This statement by Messerchmid and Bertrand is consistent with that by Winters' [5] and Sergeyevsky's [6].

The propellant consumptions of different flight segments are actually coupled with each other. Previous studies have limitations that they did not take into consideration the interaction effects of the orbital altitudes of different flight segments on the total propellant consumption. When a docking mission takes place at the lowest operational altitude, resupply vehicles consume the minimum propellant on rendezvous maneuvers; when the space station is reboosted to the highest operational altitude after this docking mission, it consumes the minimum propellant on altitude-decay maintenance. However, relative to a higher docking altitude, a lower one will lead to more propellant consumption on reboosting maneuvers after the docking mission; relative to a lower roboosting altitude, a higher one will also lead to more propellant consumption on reboosting. In consequence, the altitudes of different flight segments given by previous approaches could not be the best ones from the point view of the entire task. In addition, the selection of reboosting altitude should consider the time of the next resupply and the effect of orbital decay during this period. Too high reboosting altitude may result in active maneuvers to reduce the orbital altitude to satisfy the docking requirement [7]. Consequently, the selection of space station orbital altitudes is a multi-step decision problem with interaction relationships between neighboring flight segments.

The technique of dynamic programming is powerful and applicable to multi-step decision processes, and has been applied to the solution to some aerospace mission planning problems. Several contributions in this area should be noted here. Lantoine and Russell [8] proposed a differential dynamic programming algorithm for a low-thrust optimization problem. Rathinam et al. [9] proposed a generalized dynamic programming approach to solve an aircraft departure scheduling problem. Bousson [10] proposed a single grid point dynamic programming method for a trajectory optimization problem.

The goal of this paper is to propose a new approach for the design of space station orbits by employing the dynamic programming method. First, the long-duration orbit design process for a space station is divided into several planning periods, each of which consists of five basic flight segments. Second, each planning period is modeled as a multi-step decision process with consideration of the interaction effects of different flight segments. Third, the dynamic programming approach is used to optimize the total propellant consumption.

This paper is organized as follows. Section 2 describes the design mission of space station orbits and defines the period planning problem of the orbital design. In Section 3, the dynamic programming method is briefly presented, and the period planning problem is modeled as a dynamic decision structure; in addition, a shooting iteration method combining analytically approximate models and numerical trajectory integration is adopted to calculate the step cost. An illustrative case is presented in Section 4 to demonstrate the proposed approach. Finally, major conclusions are drawn in Section 5.

2. Space station orbit design problem

2.1. Space station orbit design mission

Based on the visiting schedule of resupply vehicles, the long-duration flight process of the space station is divided into several basic flight segments, including the altitude-lifting, autonomous flight, rendezvous and docking (RVD), and complex flight. The term “complex” denotes the integrated spacecraft composed by the space station and the resupply vehicles. In the altitude-lifting segment, the space station is lifted by maneuvers to the higher reboosting orbit altitude. In the autonomous flight segment, some maneuvers are executed to maintain the orbital altitude and to prepare the required phase angle by the next docking mission [7]. In the RVD segment, the resupply vehicle maneuvers from its injection orbit to the docking orbit, while the space station operates as a target vehicle with no maneuvers. In the complex flight segment, the