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Optimization of an orbital long-duration rendezvous mission

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ABSTRACT

The phasing segment of the rendezvous mission between a cargo spacecraft and a space station usually lasts for several weeks, and actually presents an orbital long-duration problem. In this study, this orbital long-duration problem is formulated as a mixed integer nonlinear programming (MINLP) problem in which the maneuver revolution numbers (integers), maneuver arguments of latitude and impulse magnitude are used as design variables at the same time. A hybrid approach is then proposed to solve this MINLP problem. First, a linear dynamics model considering the J_2 term of the Earth non-spherical gravity is employed to formulate an approximate phasing problem, which is optimized using a genetic algorithm. Second, a shooting iteration process considering the coupling effect between the in-plane and out-of-plane maneuvers is proposed to improve the approximate solution to satisfy the terminal conditions of the high-precision problem. The proposed approach is demonstrated for a typical two-week rendezvous phasing mission. The results show that the proposed approach can stably obtain the near optimal high-precision solution by integrating the perturbed trajectory only a few times. Furthermore, a long-duration rendezvous phasing plan is compatible with any initial phase angles that the in-plane velocity increment remains almost unchanged when the initial phase angle changes. However, under the same conditions, the out-of-plane velocity increment has considerable variations. Compared with a two-day rendezvous phasing plan, a two-week plan could have several successive coplanar launch opportunities for the chaser by aiming different terminal revolution numbers.

1. Introduction

A rendezvous and docking (RVD) mission between a cargo spacecraft and a space station, for example, the RVD between an ATV (Automated Transfer Vehicle) or HTV (H-II Transfer Vehicle) and the ISS (International Space Station) [1,2], usually lasts for several weeks. The rendezvous phasing segment consumes most of the time for a RVD mission [3], and then presents an orbital long-duration problem. For this orbital long-duration problem, in addition to impulses (continuous numbers), the maneuver revolution numbers (integers) could be used as design variables, and the continuous and discrete variables are then investigated at the same time. The optimization of a long-duration rendezvous phasing mission thus is a mixed integer nonlinear programming (MINLP) problem.

RVD has been extensively researched, and is still a hot research topic [4–8]. In a classical survey paper on RVD studies, Jezewski [9] reviewed the planning of rendezvous trajectories from both a theoretical research perspective and an operational application perspective. He pointed out that for a long-duration operational rendezvous mission, orbital perturbations must be taken into account, and that simplified relative motion models could be the foundation of rendezvous targeting algorithms. However, only a few studies have focused on orbital long-duration maneuver problems. Labourdette and Baranov [10] studied a long-duration rendezvous problem with a large initial ascending node difference for the mission involving the return of samples from Mars. They employed a near-circular relative motion model based on orbital element differences with the J_2 perturbation, to optimize the propellant cost and to analyze the relation between that cost and the terminal revolution number. Zhang et al. [11] improved Labourdette and Baranov's model, and applied it to the optimization of in-plane maneuvers in a target spacecraft's long-duration phasing mission.

Recently, the MINLP, a powerful but complicated method, has been applied to the solution of space mission planning problems. Several contributions in this area should be noted here. Ross and D'Souza [12] proposed a hybrid optimal control framework for space mission planning and applied it to the optimization of a multi-agent launch system. Luo et al. [13] proposed a hybrid strategy in the optimization of a two-day rendezvous phasing trajectory with maneuver revolution variables. Zhang et al. [14,15] employed a mixed-code genetic algorithm (GA) to optimize a multi-segment

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Nomenclature

a	semi-major axis
e	eccentricity
I_{sp}	specific impulse of thrusters
i	orbital inclination
k	iteration number of times
l	terminal revolution number changed by maneuvers
N_j	revolution number of the jth maneuver
n	mean angular motion rate
T	orbital period
t_f	end time of the rendezvous phasing mission
t_j	burn time of the jth maneuver
u_j	argument of latitude of the jth maneuver
v	orbital velocity
Δa	difference in semi-major axis
Δi	difference in orbital inclination
Δv_{yj}	in-track impulse of the jth maneuver
Δv_{zj}	cross-track impulse of the jth maneuver
$\Delta\Omega$	difference in right ascension of ascending node
$\Delta\theta$	difference in phase angle
$\Delta\xi$	difference in non-singular orbital element ξ
$\Delta\eta$	difference in non-singular orbital element η
Ω	right ascension of ascending node
ξ	non-singular orbital element, equal to $e\cos\omega$
η	non-singular orbital element, equal to $e\sin\omega$
ω	argument of perigee

Superscript

$-$	related to a mean orbital element

Subscripts

c	related to the chaser
j	related to the jth maneuver
r	related to a reference orbital element
t	related to the target spacecraft
y	related to the in-track direction
z	related to the cross-track direction
aim	related to aimed orbital elements
in	related to in-plane parameters
out	related to out-of-plane parameters

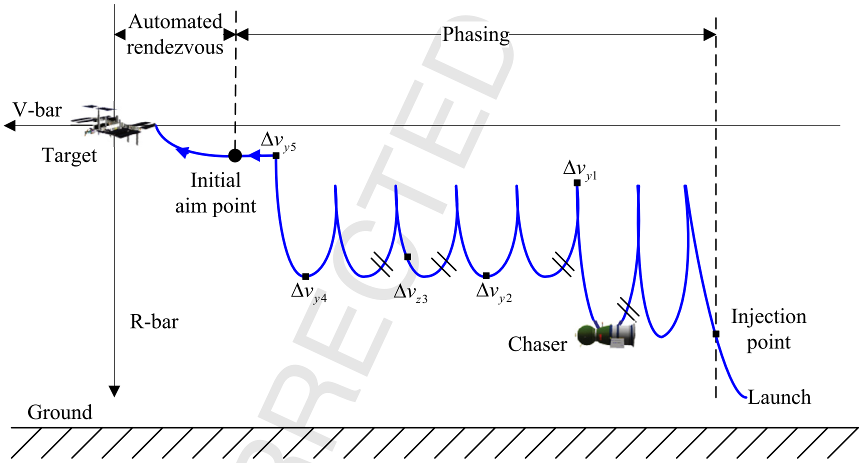

Fig. 1. Rendezvous phasing maneuver plan.

rendezvous mission, and also used the MINLP to solve a low-Earth-orbit (LEO) multi-spacecraft rendezvous problem. MINLP problems, however, remain difficult to solve due to their mixed nature and the potential for multiple local optima [16]. The idea of using maneuver revolution numbers as design variables can also be found in studies on the two-impulse multi-revolution Lambert rendezvous algorithm, in which the two maneuver revolution numbers are enumerated to find the global optimum [17].

The purpose of this paper is to propose a hybrid optimization approach for long-duration rendezvous phasing missions. To avoid having to integrate the long-duration trajectory many times, the approach first presents an approximate optimization problem, which considers the J_2 term of the Earth non-spherical gravity and the coupling effect between in-plane and out-of-plane maneuvers. The solution to the approximate problem is obtained by a GA, and then is improved to a high-precision one by a few iterations.

As mentioned above, reference [11] has employed the MINLP to solve a long-duration in-plane phasing mission of the target spacecraft. Relative to that study, this paper is actually an improvement. First, an out-of-plane maneuver is involved in this paper, which makes the problem more difficult to solve. Second, the coupling effect between the in-plane and out-of-plane maneuvers could bring difficulties to the convergence of the iteration to obtain high-precision solution, and these difficulties will be tackled in the iteration process of this paper.

2. Rendezvous phasing optimization problem

As shown in Fig. 1, the chaser, i.e. the cargo spacecraft, executes several maneuvers to acquire the initial aim point at the end of the rendezvous phasing segment, and the maneuver plan is given as follows.

The first maneuver Δv_{y1}, along the in-track direction, is executed at the apogee to adjust the altitude of the perigee.

The second maneuver Δv_{y2}, along the in-track direction, is executed at the perigee to adjust the altitude of the apogee.

The third maneuver Δv_{z3}, along the cross-track direction, is executed at the argument of latitude u_3 to adjust the orbital inclination and the right ascension of ascending node (RAAN) at the same time.

The fourth maneuver Δv_{y4}, along the in-track direction, is executed at the argument of latitude u_4 (near the perigee) to adjust the apogee altitude to the altitude of the initial aim point.

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