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Orbital rendezvous mission planning using mixed integer nonlinear programming ☆

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ABSTRACT

The rendezvous and docking mission is usually divided into several phases, and the mission planning is performed phase by phase. A new planning method using mixed integer nonlinear programming, which investigates single phase parameters and phase connecting parameters simultaneously, is proposed to improve the rendezvous mission's overall performance. The design variables are composed of integers and continuous-valued numbers. The integer part consists of the parameters for station-keeping and sensor-switching, the number of maneuvers in each rendezvous phase and the number of repeating periods to start the rendezvous mission. The continuous part consists of the orbital transfer time and the station-keeping duration. The objective function is a combination of the propellant consumed, the sun angle which represents the power available, and the terminal precision of each rendezvous phase. The operational requirements for the spacecraft–ground communication, sun illumination and the sensor transition are considered. The simple genetic algorithm, which is a combination of the integer-coded and real-coded genetic algorithm, is chosen to obtain the optimal solution. A practical rendezvous mission planning problem is solved by the proposed method. The results show that the method proposed can solve the integral rendezvous mission planning problem effectively, and the solution obtained can satisfy the operational constraints and has a good overall performance.

1. Introduction

In the rendezvous and docking (RVD) mission, for acquiring the desired docking condition, the chaser must execute many complicated operations such as orbital maneuvers, rendezvous navigation sensor switches and space–ground communications. Several station-keeping points are deployed in the rendezvous trajectory to obtain a stable orbital profile [1], and then the rendezvous process is divided into several phases such as homing, closing and approaching. Fehse [2] provided the common considerations for every rendezvous phase, and the planning of rendezvous mission is usually performed phase by phase.

To improve the rendezvous mission's overall performance, besides the parameters in each single phase, the parameters at the interfaces of different phases should also be investigated. These interface parameters include the ranges of station-keeping points, the ranges of the sensor-switching points, the number of maneuvers of different rendezvous phases, and so on. Now the design variables are composed of integers and continuous-valued numbers, and the rendezvous mission planning inevitably becomes a complicated mixed integer nonlinear programming (MINLP) problem. Recently, MINLP has been applied to the space mission planning: Ross and D'Souza [3] proposed a hybrid optimal control framework for space mission planning and the discrete variables are solved in integer programming subproblem; Luo et al. [4] proposed a hybrid strategy to optimize the rendezvous phasing trajectory, and the discrete variables are solved by integer-coded genetic algorithm. It is difficult to solve MINLP problem due to the combinatorial nature and the potential multiple local minimum points [5].

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Nomenclature

$\mathbf{C}$	covariance matrix
K_0	initial aiming point
K_i	station-keeping point
M_i	penalty coefficient of the constraint
S_j	sensor-switching point
$\mathbf{X}$	relative position and velocity
$\mathbf{X}_{design}$	design variables
dur_i	station-keeping duration
m	mass of the chaser
n_i	number of maneuvers
n_{rep}	number of repeating periods
$n_{r_{K_i}}$	serial number of the station-keeping point candidate
$n_{r_{S_j}}$	serial number of the sensor-switching point candidate
r_{K_i}	relative range of the station-keeping point
r_{S_j}	relative range of the sensor-switching point
t_{00}	initial time of the whole mission design
$t_{0n_{rep}}$	initial time to start the mission at n_{rep}th repeating period
t_{ik}	burning time of the orbital maneuver
Δt_i	orbital transfer time of a rendezvous phase
$\Delta t_{interval,j}$	time interval between the sensor transition and the next maneuver
$\Delta t_{prep,j}$	preparation time for the sensor to obtain steady filter information
$\mathbf{\Phi}$	state transition matrix of the relative position and velocity
$\mathbf{\Phi}_v$	state transition matrix of the impulse
β	orbital sun angle
$\delta\mathbf{X}$	navigation error
$\delta\Delta\mathbf{v}$	burning error
ε	spacecraft elevation angle seen from the ground station
η	sun's line of sight angle
λ_i	weight factor in the objective function
ω	mean orbital angular rate of the target

Previous studies mainly focused on the rendezvous trajectory planning for a single phase [6], especially on the fuel optimal rendezvous maneuver problem, and few studies dealt with the rendezvous mission planning which investigates single phase parameters and phase connecting parameters simultaneously. The goal of this paper is to propose a rendezvous mission planning method using MINLP, which can improve the overall performance of several rendezvous phases.

2. Rendezvous mission planning considerations

When we study orbital rendezvous, the chaser's movement is usually described in the target centered orbital coordinate system $o-xyz$, which is defined as [2]:

the z-axis, also called R-bar, is along the position vector from the target spacecraft to the earth;
the y-axis, also called H-bar, is along the opposite direction of the orbit normal;
the x-axis, also called V-bar, is toward the direction of the velocity and completes the right-handed system.

The automated rendezvous mission, which is controlled onboard, cannot be initiated until the chaser is first guided by the ground mission control center to the initial aiming point K_0. Based on the information obtained by the relative navigation sensors, the chaser's actions are automatically controlled by the onboard system after K_0.

Fig. 1 shows the process of the rendezvous mission considered in this paper: the chaser transfers from K_0 to K_3 using three sets of maneuvers with station-keeping at $K_i(i=1,2,3)$; the maneuvers are controlled onboard using the information obtained by Sensor 1, Sensor 2 and Sensor 3, with sensor-switching at S_1 and S_2; the chaser communicates with the ground stations at K_0 and K_i. The sun

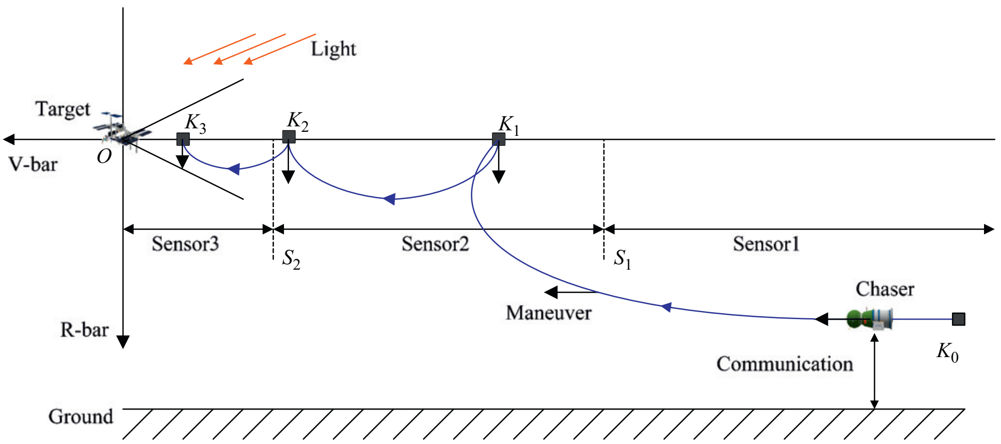

Fig. 1. The process of a rendezvous mission.