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Robust control for constant thrust rendezvous under thrust failure

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Abstract A robust constant thrust rendezvous approach under thrust failure is proposed based on the relative motion dynamic model. Firstly, the design problem is cast into a convex optimization problem by introducing a Lyapunov function subject to linear matrix inequalities. Secondly, the robust controllers satisfying the requirements can be designed by solving this optimization problem. Then, a new algorithm of constant thrust fitting is proposed through the impulse compensation and the fuel consumption under the theoretical continuous thrust and the actual constant thrust is calculated and compared by using the method proposed in this paper. Finally, the proposed method having the advantage of saving fuel is proved and the actual constant thrust switch control laws are obtained through the isochronous interpolation method, meanwhile, an illustrative example is provided to show the effectiveness of the proposed control design method.

1. Introduction

As well-known, there are many tasks to be conducted in space such as building and operation of the international space station, inspection and repair of orbiting satellites and conducting lunar/planetary explorations. Some of these tasks are currently conducted by astronauts. However, most of these tasks are highly risky and expensive. Therefore space robot is an indispensable tool for future space activities.[1,2] Therefore, space robot's autonomous rendezvous is a crucial phase for many important astronautic missions such as intercepting, repairing, saving, docking, large-scale structure assembling and satellite networking.

During the last few decades, the problem of autonomous rendezvous has been extensively studied and many results have been reported.[3–5] For example, the optimal impulsive control method for spacecraft rendezvous is studied in Ref. [6]; adaptive control theory is applied to the rendezvous and docking problem in Ref. [7]; an annealing algorithm method for rendezvous orbital control is proposed in Ref. [8]; a new rendezvous

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guidance method based on sliding-mode control theory can be found in Ref. [9]. Although there have been many results in this field, the rendezvous orbital control problem has not been fully investigated and still remains challenging. Both impulsive thrust and the continuous thrust assumptions in these results have been exploited through the Pontryagin's maximum principle respectively.[10–12] In actual practice, however, the thrusts of the spacecraft are constant thrusts, therefore, maneuver during rendezvous and docking operations cannot be normally considered as continuous thrust maneuver or impulsive maneuver.[13–15] In our previous study,[16] constant thrust fuel-optimal control for spacecraft rendezvous was studied according to Clohessy–Wiltshire (C–W) equation and the analytical solutions. But the traditional open-loop control method used in our previous studies is not applicable while they are often utilized during the long-distance navigation process. To overcome this problem, a robust closed-loop control laws for constant thrust rendezvous to enhance the orbital control accuracy is proposed in this paper. And the fuel consumption of constant thrust is less than that of the continuous thrust by using the method proposed in this paper.

The purpose of this paper is to study the constant thrust rendezvous under thrust failure. In order to compare the fuel consumption under the theoretical continuous thrust and the actual constant thrust, a new algorithm of constant thrust fitting is proposed by using the impulse compensation method. The optimal fuel consumption and the actual working times of the thrusters in three axes can be respectively calculated by using the time series analysis method.

2. Multi-objective robust controller design

There are ten thrusters installed on the space robot as shown in Fig. 1, where thruster 9 and thruster 10 are symmetric, and the thrust of the ith thruster is defined as F_i $(i = 1, 2, \ldots, 10)$.

The relative motion coordinate system can be established as follows. Firstly, the target spacecraft is assumed as a rigid body and in a circular orbit, and the relative motion can be described by C–W equation. Then, the centroid of the target spacecraft O_T is selected as the origin of coordinate, the x-axis is opposite to the target spacecraft motion, the y-axis is from the center of the Earth to the target spacecraft and the z-axis is determined by the right-handed rule. Suppose that thrust failure in the y-axis is shown in Eq. (1):

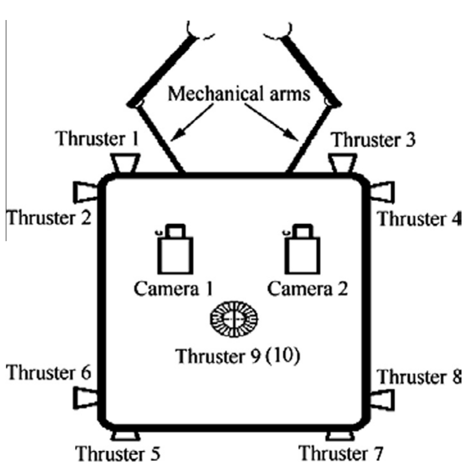

Fig. 1 Space robot.

$$\begin{cases} \ddot{x} - 2\omega\dot{y} = \dfrac{F_x + \eta_x}{m} \\ \ddot{y} + 2\omega\dot{x} - 3\omega^2 y = \dfrac{\eta_y}{m} \\ \ddot{z} + \omega^2 z = \dfrac{F_z + \eta_z}{m} \end{cases} \tag{1}$$

where x, y and z are the components of the relative position in corresponding axes, ω the angular velocity, F_x and F_z the vacuum thrust of the space robot, η_x, η_y, η_z the sum of the perturbation and nonlinear factors in the x-axis, y-axis and z-axis, respectively, and m the mass of the space robot at the beginning of the rendezvous. The state variable is defined as $\boldsymbol{x}(t) = [x, y, z, \dot{x}, \dot{y}, \dot{z}]^{\mathrm{T}}$, the control input vector is $\boldsymbol{u}(t) = [F_x,\ 0,\ F_z]^{\mathrm{T}}$, and the vector of the perturbation and nonlinear factors is defined as $\boldsymbol{\eta}(t) = [\eta_x, \eta_y, \eta_z]^{\mathrm{T}}$, then the state equation can be transformed as

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{A}_0\boldsymbol{x}(t) + \boldsymbol{B}_0(\boldsymbol{u}(t) + \boldsymbol{\eta}(t)) \tag{2}$$

where

$$\begin{cases} \boldsymbol{A}_0 = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 2\omega & 0 \\ 0 & 3\omega^2 & 0 & -2\omega & 0 & 1 \\ 0 & 0 & -\omega^2 & 0 & 0 & 1 \end{bmatrix} \\ \boldsymbol{B}_0 = \dfrac{1}{m}\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \end{cases} \tag{3}$$

Suppose that the time of rendezvous maneuver is T_{r} and the shortest switching time interval of thrust is ΔT, there are M shortest switching time and N target maneuver positions, and $T_{\mathrm{r}i}$ $(i = 1, 2, \ldots, N)$ represents the time of the ith thrust arc, $M_{\mathrm{r}i}$ $(i = 1, 2, \ldots, N)$ represents the number of the shortest switching time M_{r} in the ith thrust arc.

$$T_{\mathrm{r}} = M_{\mathrm{r}}\Delta T \tag{4}$$

with

$$\begin{cases} T_{\mathrm{r}i} = M_{\mathrm{r}i}\Delta T \\ M = M_{\mathrm{r}1} + M_{\mathrm{r}2} + \cdots + M_{\mathrm{r}N} \end{cases} \quad (i = 1, 2, \ldots, N) \tag{5}$$

The process of collision avoidance maneuver can be considered as the system state variables changing from a non-zero initial state $\boldsymbol{x}(0)$ to a desired state $\boldsymbol{x}(T) = \boldsymbol{0}$, where T is the time required for collision avoidance maneuver. To make the controller complies with engineering practice, we should consider the following two important questions:

(1) Parameter uncertainty. Due to measurement errors and the complex interactions between celestial bodies, it is difficult to accurately obtain the angular velocity of the target spacecraft. ω_0 is defined as the theoretical angular velocity of the target spacecraft, and $\Delta\omega$ the uncertainty of the parameters, then the actual angular velocity of the target spacecraft is