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Robust reliable control for autonomous spacecraft rendezvous with limited-thrust ☆

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ABSTRACT

This paper investigates the problem of robust reliable control for the spacecraft rendezvous with limited-thrust. Based on the Clohessy–Wiltshire (C–W) equations and by considering the uncertainties and the possible failures, the dynamic model for spacecraft rendezvous is proposed, and the orbital transfer control problem is transformed into a stabilization problem. Then, by a Lyapunov approach, the existence conditions for admissible controllers are formulated in the form of linear matrix inequalities (LMIs), and the controller design is cast into a convex feasibility problem subject to LMI constraints. With the obtained controllers, the rendezvous can be accomplished with the limited-thrust in spite of the possible thruster failures. The effectiveness of the proposed approach is illustrated by simulation examples.

1. Introduction

As is well known, 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 attracted considerable attention and many results have been reported. For example, the optimal impulsive control method for spacecraft rendezvous is studied in [13,16,21]; adaptive control theory is applied to the rendezvous and docking problem in [20]; an annealing algorithm method for rendezvous orbital control is proposed in [15]; a new rendezvous guidance method based on sliding-mode control theory can be found in [5]; and in [22], the problem of rendezvous is cast into a stabilization problem analyzed by Lyapunov theory. Although there have been many results in this field, the rendezvous orbital control problem has not been fully investigated and still remains challenging.

During the rendezvous, many uncertain factors, such as the inaccuracies of the aero-parameters, the errors of the equipment and the variation of the mass, degrade the safety and the precision of the rendezvous. In particular, due to the errors of the detection equipment and the external perturbations, it is hard to determine the accurate angular velocity of the target, which is a very important parameter for the calculation of the control input force. Therefore, guaranteeing robustness for the uncertainties is a challenge in the study of the rendezvous orbital control problem. In recent years, some results have been reported to deal with the uncertainties, see, for instance [9,7,18,19,25]. Nevertheless, for the spacecraft rendezvous problem, the uncertainties are always studied separately from other requirements, and it is necessary to take the design requirements into consideration simultaneously.

On the other hand, the autonomic systems are always vulnerable to various failures in practical applications. Due to the complexity of spacecraft rendezvous process, it is hard to completely avoid the failures existing in the thrusters, which have much to do with the safety and accuracy of the rendezvous. Hence, in addition to considering the uncertainties mentioned above, reliability against the possible thruster failures is also a major challenge in the autonomous rendezvous problem. In the last decades, reliable control has attracted many researchers and a number of results have been reported. For example, [23,24] present the reliable controller design methods for linear systems, such that the systems can be stabilized and the performances are ensured in spite of some admissible control component outages; the controller design problem for network with random packet losses or missing measurements is studied in [27–30]; in [32], a pre-compensator is utilized to design a reliable state feedback controller for the system with actuator redundancies. In most of the studies, it is often assumed that the signals of the sensors or the outputs of the actuators become zero when failures occur. This modeling method can simplify the controller synthesis. However, it is significant to adopt a more general model to describe the failures with scaling factors with upper and lower bounds. It is worth noticing that such a

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model is seldom utilized in the studies of reliable controller design problem for spacecraft rendezvous.

Besides the uncertainties and the possible failures, it is also necessary to take the constraints of limited-thrust into consideration in the study of spacecraft rendezvous problem. In most of the practical aerospace missions, there are many hard constraints for the weight of the equipment and the quantity of the fuel. Therefore, orbital transfer thrusters of the spacecraft have limited power and limited thrust. In recent years, the problem of orbital transfer with limited-thrust has been studied by many researchers. For instance, a control-theoretic framework for low-thrust orbital transfers using orbital elements is derived in [11]; the problem of aero-assisted or gravity-assisted orbital transfers with limited-thrust is studied in [1,4]; evolutionary programming and nonlinear collocation method have been investigated for the problem of orbital transfer with low-thrust [3,12]. It should be noticed that most of the studies in this field focus on the control methods for sole spacecraft, and these methods are not suitable for spacecraft rendezvous because of the relative motion between the chaser and the target during the rendezvous. Therefore, the rendezvous orbital controller design with limited-thrust is still an important problem to be solved.

Motivated by the above discussions, in this paper we study the reliable controller design problem for spacecraft rendezvous with parameter uncertainties and limited-thrust. Based on the Clohessy–Wiltshire (C–W) equations, the uncertain rendezvous models with possible thruster failures are established. The autonomous rendezvous problem is transformed into a stabilization problem for the relative motion system. Then, the reliable state feedback controller design method is developed by a Lyapunov approach. The existence conditions for the admissible reliable controllers, with which the uncertain relative motion system can be stabilized with the limited control input in spite of the failures, are formulated in the form of linear matrix inequalities (LMIs), and the controller design problem is cast into a convex feasibility problem subject to LMI constraints. If the feasibility problem is solvable, the desired controller can be constructed. An illustrative example is provided to show the effectiveness and advantage of the proposed control design method.

The rest of this paper is organized as follows. In Section 2, the dynamic model of spacecraft rendezvous is established, and the robust reliable controller design problem is formulated. Section 3 presents controller design method. Then, an example is given to illustrate the applicability of the proposed approach in Section 4. Finally, Section 5 draws the conclusion.

Notations: The notation used throughout the paper is fairly standard. The superscript “T” stands for matrix transposition; $\mathbb{R}^n$ denotes the n-dimensional Euclidean space and $\mathbb{R}^{n\times m}$ denotes the set of all $n\times m$ real matrices; $\|\cdot\|$ refers to either the Euclidean vector norm or the induced matrix 2-norm. For a real symmetric matrix W, the notation $W>0$ ($W<0$) is used to denote its positive- (negative-)definiteness. diag$\{\ldots\}$ stands for a block-diagonal matrix. For any matrix S, sym$\{S\}$ means $S+S^T$. In symmetric block matrices or complex matrix expressions, we use an asterisk ($*$) to represent a term that is induced by symmetry. I and 0 denote the identity matrix and zero matrix with compatible dimensions, respectively. Matrices, if their dimensions are not explicitly stated, are assumed to be compatible for algebraic operations.

2. Problem formulation

In this section, based on the C–W equations, the relative motion model is established by considering the norm-bounded parameter uncertainties and the possible thruster failures. Then, the reliable control problem under study in this paper is formulated based on the model.

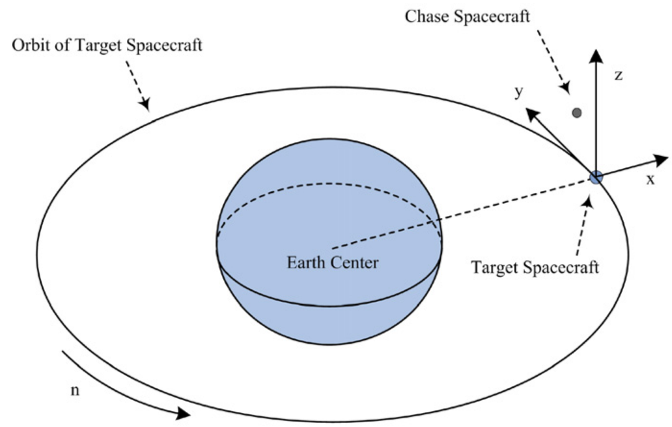

Fig. 1. Spacecraft rendezvous.

2.1. Coordinate of the spacecraft rendezvous

A basic model for the study of relative motion is given by C–W equations, derived by Clohessy and Wiltshire in 1960 [2]. The model based on C–W equations has been widely used to study the relative motion between two neighboring spacecraft when the target orbit is approximately circular and the distance between them is much smaller than the orbit radius [10,13,15–17,21,31].

The spacecraft rendezvous system is illustrated in Fig. 1. We assume that the two spacecraft (Target and Chaser) are adjacent, and the orbital coordinate frame in our study is a right-handed Cartesian coordinate, with origin attached to the target spacecraft center of mass, x-axis along the vector from Earth's center to the target's center of mass, y-axis along the target orbital circumference in the direction of target velocity, and z-axis completing the right-handed frame.

According to the C–W equations, the relative dynamic motion between the chaser and the target can be depicted as:

$$\begin{cases} \ddot{x}-2n\dot{y}-3n^2x=\dfrac{1}{m}u_x, \\ \ddot{y}+2n\dot{x}=\dfrac{1}{m}u_y, \\ \ddot{z}+n^2z=\dfrac{1}{m}u_z, \end{cases} \tag{1}$$

where x, y, z are the components of the relative position, n is the constant angular velocity of the target spacecraft moving around the earth, m is the mass of the chase spacecraft, u_i ($i=x,y,z$) is the ith component of the specific control force acting on the chaser.

2.2. Thruster failure model with uncertainty

According to (1), by assuming that the initial orbits of the chaser and the target are coplanar ($x\neq 0$, $y\neq 0$, $z=0$), the state vector can be defined as $\mathbf{q}(t)=[x,y,\dot{x},\dot{y}]^T$. Then, the whole rendezvous process can be described by the transformation of state vector $\mathbf{q}(t)$ from nonzero initial state $\mathbf{q}(0)$ to the terminal state $\mathbf{q}(t_m)=0$, where t_m is the rendezvous time. Furthermore, by defining control input vector $\mathbf{u}^f(t)=[u_x,u_y]^T$ and output vector $\mathbf{f}(t)=[x,y]^T$, we have

$$\begin{cases} \dot{\mathbf{q}}(t)=(A+\Delta_A)\mathbf{q}(t)+B\mathbf{u}^f(t), \\ \mathbf{f}(t)=C\mathbf{q}(t), \end{cases} \tag{2}$$