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Integrated robust adaptive tracking control of non-cooperative fly-around mission subject to input saturation and full state constraints

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ARTICLE INFO

Article history:
Received 6 January 2018
Received in revised form 16 April 2018
Accepted 20 May 2018
Available online xxxx

Keywords:
Non-cooperative fly-around mission
Integrated robust tracking control
Adaptive backstepping control
Input saturation
Full state constraints

ABSTRACT

This paper investigates the relative position and attitude tracking control of non-cooperative fly-around mission in the presence of parameter uncertainties, external disturbances, input saturation and full state constraints. Firstly, an integrated and coupled 6 DOF relative motion dynamic model is established, which is consisted of relative position model depicted in the line-of-sight (LOS) frame and relative attitude model described by Modified Rodriguez parameters (MRPs). Subsequently, by using the backstepping control method, an integrated robust adaptive anti-windup control scheme is proposed, in which uncertain parameters and unknown upper bound of the disturbances are estimated by adaptive technique, and the adverse effects caused by input saturation are reduced by the designed anti-windup compensator. To guarantee the full state constraints satisfied all the time, the barrier Lyapunov function method is incorporated into the backstepping control design. Rigorous stability proofs show that the designed robust adaptive controller guarantees that the relative motion states not only can be restricted in the prescribed constraint regions, but also can converge into the small regions with good robustness. Finally, numerical simulation results demonstrate the effectiveness and performance of the designed control scheme.

1. Introduction

Autonomous rendezvous and proximity operation have become an key technology in many space on-orbit serving missions, such as capturing malfunctioned satellite, repairing and refueling, removing space debris in orbit [1]. Especially for the case of non-cooperative target, rendezvous and proximity operation will suffer from huge risks and challenges since the target's motion information are unknown completely for the chaser spacecraft [2,3]. Therefore, to guarantee that on-orbit serving missions can be implemented safely and successfully, spacecraft fly-around mission with non-cooperative target is an important process, in which the target can be observed and monitored quickly and comprehensively such that some characteristics can be extracted for cooperative measurement and close range rendezvous [4].

In the spacecraft fly-around motion, to achieve effective observation and monitor for target spacecraft, the attitude of the chaser should be adjusted such that the sensor devices loaded on the chaser, such as charge-coupled device (CCD) cameras, can keep orientation to the target all the time. Therefore, to accomplish non-cooperative fly-around mission, not only position control but also attitude orientation control should be considered. Traditionally, the relative position control and attitude control are considered independently. For instance, some relative position controllers for spacecraft translational motion were proposed by using optimal impulse control [5], robust H_∞ control [6], gain scheduled control [7], adaptive control [8]. Meanwhile, some attitude controllers for spacecraft rotational motion were designed by using finite time control [9], sliding mode control [10], fault-tolerant control [11], passivity-based control [12]. However, the separate control strategy suffers from some disadvantages, such as low control precision and efficiency [13]. To overcome these drawbacks, integrated position and attitude control design with united control framework is considered. In [14], three nonlinear control schemes by using passivity-based PD + control, sliding mode control and integrator backstepping control method were proposed for 6 DOF spacecraft formation flying. In [15], based on the exact linearization method, integrated attitude and position adaptive controller was designed for spacecraft fly-around motion. However, the naturally coupled effects between translational motion and rotational motion are ignored in [14,15]. In the spacecraft fly-around motion, relative position motion and attitude motion are strongly coupled, which is

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https://doi.org/10.1016/j.ast.2018.05.033
1270-9638/© 2018 Published by Elsevier Masson SAS.

Please cite this article in press as: Y. Huang, Y. Jia, Integrated robust adaptive tracking control of non-cooperative fly-around mission subject to input saturation and full state constraints, Aerosp. Sci. Technol. (2018), https://doi.org/10.1016/j.ast.2018.05.033

mainly manifested in two aspects: one is the dynamic coupling effects between relative position and attitude model since the desired attitude orientation is determined by the relative position in the fly-around motion. The other is the control input coupling effects since the control force and torque for relative position and attitude motion are provided by same actuators. Thus, to achieve high control precision and efficiency, integrated attitude and position control schemes should be designed in the fly-around motion. In addition, since the target is non-cooperative, whose orbital parameters are unknown, then the relative position dynamic model based on C–W equation [16] and T–H equation [17], which are assumed that target spacecraft moves in circular orbit and elliptical orbit respectively, will not be suitable for non-cooperative fly-around motion. Thus, how to describe and construct the coupled 6 DOF relative motion model for non-cooperative fly-around motion is also an important and challenging problem.

In the spacecraft fly-around motion, due to the fuel consumption or load drift in the rotational motion, the mass and inertia matrix of chaser spacecraft may change, which leads to the parameter uncertainties [18]. Furthermore, the relative position motion and attitude motion are inevitable influenced by the unknown disturbances in the space environment, such as orbital perturbation, solar radiation. In addition, there are some measurement errors in the relative motion state information due to no artificial makers for cooperative measurements [19]. To reject the parameter uncertainties, disturbances and measurement errors, a robust integrated position and attitude control design scheme is required.

Actuator saturation is a ubiquitous problem in the spacecraft control system due to the constraints of the thrust equipment and the limit quantity of fuel. The saturation constraints of actuator may degrade and deteriorate the control performance of the closed-loop system [20]. Thus, it is necessary to consider actuator saturation in the control design. In addition, since the CCD sensor devices have field of view constraints, to ensure the effective observation and measurement, non-cooperative target should be located in the line-of-sight cone of the CCD sensor devices, which implies that the attitude errors between the practical sensor direction and desired direction should be constrained in the prescribed ranges. To avoid the danger of collision, the relative position states are constrained in the safe range. Moreover, from the engineering viewpoint, the translational velocity and rotational angular velocity also should be constrained due to the measurement range limitations of the velocity sensors and gyros [21]. Thus, with full state constraints and control magnitude constraints considered, the safety and reliability of non-cooperative fly-around motion can be guaranteed. For spacecraft state constraints or control constraints problem, there are some related results in the literatures. For instance, in [22], a robust nonlinear control scheme by using barrier Lyapunov function (BLF) was proposed to achieve the attitude stabilization under assigned velocity and control constraints. In [23], a model predictive control approach was developed for spacecraft rendezvous and proximity maneuvering under the thrust magnitude, position and velocity constraints. However, only relative position control or attitude control is considered in [22,23], essentially ignoring the natural coupling effects of spacecraft relative motion.

Motivated by above discussion and analysis, we will consider the integrated relative position and attitude control for non-cooperative fly-around mission in the presence of parameter uncertainties, disturbances, input saturation and full state constraints. The main contributions of this paper are stated as follows:

Firstly, an integrated and effective 6 DOF relative motion model by considering the requirements of the line-of-sight (LOS) orientation and the coupling effects are established, which is constructed by relative position model expressed in the LOS coordinate frame and relative attitude model described by Modified Rodriguez parameters (MRPs). Compared with 6 DOF relative motion model given in [24–26], no target's absolute motion information and orbital parameter information are involved in the established relative motion model, which can be suitable for non-cooperative fly-around motion.

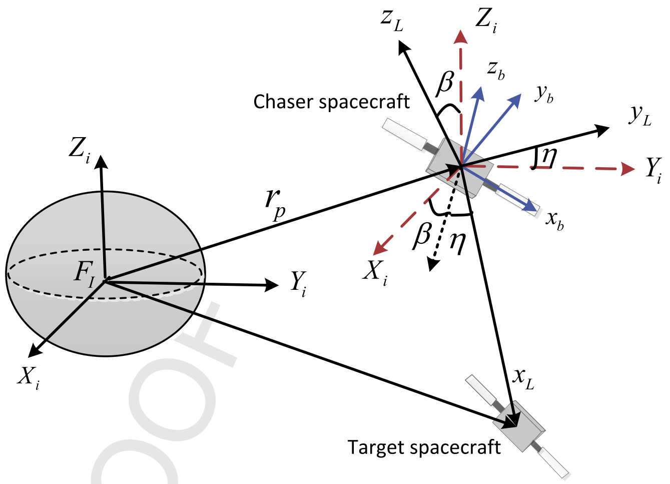

Fig. 1. Reference coordinate frame.

Secondly, by using the backstepping control method, integrated relative position and attitude control scheme is developed based on one unified robust adaptive anti-windup control framework, in which the barrier Lyapunov function is incorporated into each step of the backstepping design to satisfy the full state constraints and anti-windup compensator is designed to reduce the adverse effects of the control saturation.

Thirdly, to compensate the parameter uncertainties and disturbances, an adaptive control law is designed to estimate the unknown parameters and the upper bound of the disturbances. Compared with results in [28] and [27], where the number of the estimated parameters are 324 and 15, respectively, the proposed adaptive control laws can decrease the number of the estimated parameters from 324 and 15 to 3, which can reduce the computation burden of the controller largely.

The rest of the paper is organized as follows. In Section 2, the coupled 6 DOF relative motion model for non-cooperative fly-around motion is established. The robust controller design and the stability analysis are presented in Section 3. Numerical simulations are given in Section 4 to verify the effectiveness of the controllers. Finally, some conclusions are summarized in Section 5.

Throughout this paper, the following notations are used. Let $\mathbb{R}^{n\times n}$ and $\mathbb{R}^n$ be the set of $n \times n$ real matrices and n dimensional real vectors, respectively, $I_{n\times n}$ be n dimensional identity matrix, and I_i be the diagonal matrix with zero diagonal elements except the ith diagonal element equal to 1 of compatible dimensions. A^T and A^{-1} denote the transposition inverse operations of matrix A, respectively. $|\cdot|$ represents the absolute value of a scalar and $\|\cdot\|$ denotes the Euclidean norm of vector or the induced 2-norm of matrix.

2. Problem formulation

2.1. Coordinate reference frames

For non-cooperative spacecraft fly-around mission, the following coordinate frames are introduced, which are shown in Fig. 1:

1) The Earth centered internal (ECI) frame is denoted as F_I, whose origin is located in the center of the mass of the earth with X_i axis towards the vernal equinox, Z_i axis towards celestial north, and Y_i axis conformed to a right-handed orthogonal frame.

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