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Robust adaptive integrated translation and rotation control of a rigid spacecraft with control saturation and actuator misalignment

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ABSTRACT

This paper handles the integrated translation and rotation tracking control problem of a rigid spacecraft with unknown mass property, actuator misalignment and control saturation. In view of the system natural coupling, the coupled translational and rotational dynamics of the spacecraft is developed, where a thruster configuration with installation misalignment is taken into account. By using anti-windup technique and backstepping philosophy, a robust adaptive integrated control scheme is proposed such that the spacecraft is able to track the command position and attitude signals in the presence of external disturbance, unknown mass property, thruster misalignment and control saturation. Within the Lyapunov framework, the uniformly ultimate boundedness of the system states is guaranteed. In particular, given the nominal case, the asymptotic convergence of the system states can be further ensured by the proposed control scheme. Finally, numerical simulation demonstrates the effect of the designed control strategy.

1. Introduction

Translation and attitude control of spacecraft is of great importance in many space missions, especially proximity operations including space debris removal, in-orbit maintenance, spacecraft formation flying (SFF) and space station installation [1–18]. Traditionally, neglecting the mutual couplings, orbit and attitude motions of spacecraft were often separately considered and controlled, which was easy to implement but hard to provide high control accuracy to meet the requirements of future space missions [5,7,9,10,17]. The translation dynamics and the attitude dynamics of a spacecraft are coupled mainly due to the following reasons: (1) the translational dynamics involves the rotational motion of the spacecraft and (2) actuator configuration to control the spacecraft leads to dynamic coupling between rotation and translation; moreover, the unbalanced torques caused by actuator misalignment are prone to incur undesirable angular rotations. Consequently, in order to achieve control requirements of future missions with high control accuracy and maneuverability like proximity operations, the translation and the rotation of the spacecraft should be simultaneously taken into consideration. This interesting and challenging problem has received increasing attention in recent years [1–18].

For a single rigid spacecraft, sliding mode control was used to enable position and attitude maneuvers simultaneously [1]. In [2], a fuel suboptimal feedback controller was found using the state-dependent Ricatti equation method. Zhang et al. [3] employed finite-time control

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technique to deal with integrated position and attitude robust maneuver of a rigid spacecraft. While in view of multi-spacecraft missions, an output feedback tracking control was designed to ensure the global asymptotic convergence of the relative position and attitude errors; based on the same model, Pan [4] synthesized an adaptive integrated tracking control law to achieve same objectives; Xu et al. [5] designed a globally stable chattering free sliding mode robust controller to make both position and attitude tracking error converge to equilibrium point, where a thruster layout was taken into account. Curti et al. [6] also took into account a thruster layout to guarantee Lyapunov-stable integrated rotation and translation tracking. Xin and his colleagues presented a nonlinear integrated position and attitude suboptimal control method, namely $\theta{-}D$ technique, to finish tumbling target approach [7]. Kristiansen et al. [8] utilized three nonlinear state feedback control, involving passivity-based PD+ controller, sliding surface controller, and integrator backstepping controller, to solve the problem of tracking relative 6-DOF motion in a leader-follower spacecraft formation. In the same mission, Zhang et al. [9] further considered the control constraint, while Wu et al. [10] dealt with attitude angular velocity constraint. Subbarao et al. [11] considered the control problem of motion synchronization of free-flying robotic spacecraft and serviceable floating objects in proximity operations. Shan [12,13] presented adaptive synchronization control schemes for desired attitude and position tracking of SFF. Chung et al. [14] focused on the same problem with Lagrangian approach. Sun et al. [15] proposed a composite controller based on finite time technique and feedforward compensation to deal with 6-DOF SFF control problem. For the same problem, Wang et al. designed robust adaptive terminal sliding mode controller and model-independent PD-like controller by dual quaternion representation in [16,17], respectively. Boyarko et al. [18] designed an optimal rendezvous trajectories of a controlled spacecraft and a both translational and rotational dynamics are considered.

In the context of the integrated translation and rotation control of the spacecraft, although many works have been done, several important issues in applications should be further taken into consideration:

1. Control saturation: In practice, thrust generated by propulsion units for orbital control or attitude control is often limited. Without considering the influence of input constraints, the actual thrust would not match up with the anticipated control input, which may result in a poor control precision, or even cause the system unstable [19–21]. Meanwhile, long-time saturation will do a great harm to actuators, and thus should be avoid or reduced as much as possible.
2. Actuator misalignment: The actuator misalignment often occurs when actuators are fixed on the body of the spacecraft, which introduces the control-dependent disturbance into the coupled dynamics. Since it easily deviates the real control input from the desired value and deteriorate the system performance [22,23], the affection caused by the actuator misalignment should be suppressed.
3. Besides, unknown mass property, involving inertia matrix and mass of the spacecraft, and external disturbances would also reduce the control accuracy and thus should not be ignored during the control system design.

In fact, it is not hard to only tackle one of the above problems with some control technique. However, the situation will get worse and be hard to deal with once all the above factors should be taken into account. Thus it is necessary and worthwhile to focus on the robust integrated position and attitude tracking control problems with the simultaneous consideration of external disturbance, unknown mass property, thruster misalignment and control saturation. This forms the motivation of the present research.

In this paper, we focus on the control problem that a rigid spacecraft with actuator misalignment and control saturation will be driven to track the command position and attitude, in the presence of unknown mass property and external disturbance. To this end, the coupled translation and rotation error dynamics of a rigid spacecraft is formulated first, where a thruster layout is considered to provide directional forces and attitude control torques; moreover, the thruster misalignment and magnitude limit is analyzed and further introduced into the coupled dynamics as a control-dependent disturbance. In the sequel, the anti-windup technique and the backstepping philosophy are synthesized to construct a robust adaptive integrated translation and rotation control scheme, where an auxiliary signal is introduced to compensate for the control saturation effect; a first-order filter is used to facilitate the computations of the derivative of the command state, and a projection type adaptive law is utilized to estimate unknown parameters. It follows that the uniform ultimate bounded stability of the closed-loop system is guaranteed within the Lyapunov framework. In particular, given the nominal case (only the unknown parameters exist), the asymptotic convergence of the system states can be further ensured by the proposed control scheme. Finally, a numerical simulation demonstrates the effect of the designed control strategy.

The remainder of this paper is organized as follows. In Section 2, the translational and rotational coupled error dynamic model of the spacecraft is stated. Then, a robust adaptive integrated translational and rotational control strategy is developed for the coupled system in Section 3. Next, numerical simulation results applying the proposed control law to a spacecraft to track command position and attitude trajectories are presented for a scenario in Section 4. Finally, Section 5 draws the conclusions..

2. Problem formulation

2.1. Coupled dynamics

To form the basis of the coupled error dynamics modeling, several frames are presented first, as shown in Fig. 1. Let $\mathcal{F}_i$ be an inertial frame. The spacecraft is