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Research Article

Robust attitude control design for spacecraft under assigned velocity and control constraints

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ABSTRACT

A novel robust nonlinear control design under the constraints of assigned velocity and actuator torque is investigated for attitude stabilization of a rigid spacecraft. More specifically, a nonlinear feedback control is firstly developed by explicitly taking into account the constraints on individual angular velocity components as well as external disturbances. Considering further the actuator misalignments and magnitude deviation, a modified robust least-squares based control allocator is employed to deal with the problem of distributing the previously designed three-axis moments over the available actuators, in which the focus of this control allocation is to find the optimal control vector of actuators by minimizing the worst-case residual error using programming algorithms. The attitude control performance using the controller structure is evaluated through a numerical example.

1. Introduction

Attitude control of a spacecraft in general is the process of reorienting it to a desired attitude or orientation, and it plays an important role in achieving spacecraft operational services, such as remote sensing, communication, international space station supplying and repairing, and varieties of space-related researches. These orbiting operations require achieving these maneuvers in a very high accuracy, but under the physical constraint of sensor whose output measurement, such as available on-board angular velocity, is restricted and bounded. Moreover, for such precise rotational maneuvers, the dynamics of the spacecraft is strongly nonlinear in nature and also is affected by various disturbances from the environment that influence the mission objectives significantly. In addition, the actuators are not able to provide any requested joint torque and the available actuator torque amplitude is limited in an actual spacecraft. Furthermore, the actuator uncertainties due to misalignment during installation and magnitude deviation increase further the complexity of the attitude control system. All these in a practical and realistic environment cause a considerable difficulty in the design of attitude control system for meeting high precision pointing requirement under assigned angular velocity and desired control performance during space missions, especially when all these issues are treated simultaneously.

Recently, many studies related to attitude control law design have been extensively studied in literature based on several inspired approaches, such as optimal control [1,2], nonlinear feedback control [3–6], adaptive control [7,8], and robust control or their integrated applications [9–12]. Generally speaking, most or partial previous works can deal with external disturbances and uncertainties in some degree, but there is no means of incorporating constraints on individual angular velocity. More specially, for some practical applications such as rendezvous of space shuttle with International Space Station, etc., the constraints on rigid body angular velocity components might be required and the assigned velocity constraints is therefore treated as a set of specifications. In Ref. [13], a nonlinear feedback control logic which accommodates the actuator and sensor saturation limits was introduced. However the uncertainties and external disturbances were not considered. Accordingly, the angular velocity constraints problem was also taken into account in Refs. [14–17] with various methods; especially, Karami and Sassani [15] utilized the log-term in the Lyapunov function to analyze Hu [16] and prove the system stabilization by dealing with the velocity constraints effectively, which is motivated by the Lyapunov function introduced in Ref. [17].

However, the above-mentioned studies have been derived under the implicit assumptions that the actuators are able to

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provide any requested joint torque, and also the torque axis directions and/or input scaling of the actuators (such as reaction wheels) are exactly known. These assumptions are rarely satisfied in practice because of misalignment of the actuators during installation, and magnitude error due to aging and wearing-out of the mechanical and electrical parts, etc. Moreover, for the requirement of high pointing accuracy of some special orbiting missions and the limitation of the energy, even small misalignments of the actuator axes can be detrimental and inappropriate. Adaptive control combined with other effective method has been adopted to handle the actuator misalignments and magnitude deviation [18,19]. However, due to complexity and computation burden of this method, it is hard to apply in practice. To solve this problem effectively, we develop in this paper a new control allocation scheme by explicitly considering these constraints. In general, modern spacecraft often uses redundant actuators for safety to achieve the orbiting operations, that is to say, it is an over-actuated system, and there are available freedoms for designing a better control system with a better use of these hardware redundancies. To make use of these actuator redundancies, control allocation technique is one natural solution for achieving desired control objective based upon the baseline controller.

Control allocation is able to distribute the total control demand derived from the baseline controller design among the individual actuators while accounting for their constraints under redundant actuators [20]. Loosely speaking, the over-actuated control system consists of using possibly desired control laws, which specify only the total control effort to compensate the system, and separately, one of suitably distributing the desired total control command over the available actuators, from which the actuator constraint like saturation can be taken into account explicitly. Several approaches on control allocation have been investigated in the last decades, such as: daisy chaining [21], linear or nonlinear programming based optimization algorithms [22], direct allocation [23], dynamic control allocation [20,24], etc. Most or partial previous works study linear control allocation by programming algorithms, which can be iteratively conducted to minimize the error between the commands produced by virtual control law and the moments produced by practical actuator combinations. Recently, a robust least-squares based control allocation scheme applied for flight control system with an uncertain control effectiveness matrix is investigated in Ref. [25], which is inspired by Refs. [26,27], in which the robust least-squares problems are considered with the coefficient matrices as unknown but bounded. However the actuator magnitude errors or loss of control effectiveness are not considered.

In this work, an attempt is made to provide a simple and robust nonlinear feedback control strategy incorporating with a modified robust least-squares control allocation scheme for spacecraft attitude stabilization system under the constraints of bounded angular velocities, external disturbances, actuator misalignments and magnitude errors, and control saturation as well. For the nonlinear control law, it can achieve the desired rotation maneuvers under assigned angular velocity and can be robust to the external disturbances by involving a nonlinear term. For the control allocation method, it can deal with the problem of distributing the total nonlinear control command into the individual actuator properly by involving a control allocator, whose purpose is to find the optimal control vector of actuators by minimizing the worst-case residual, under the condition of the uncertainties included in actuator configuration matrix, torques magnitude errors and control constraints like saturation. A key feature of the designed controller ensures both attitude and bounded velocities convergence with simple design procedures and inexpensive online computations, which is of great interest for aerospace industry for real-time implementation especially when onboard computing power is limited for instance. The benefits of the proposed control method are analytically authenticated and also validated via simulation study. The paper is organized as follows. The next section states spacecraft modeling and control problem formulations. Attitude control laws are derived in Section 3. In Section 4, a novel control allocation design under actuator uncertainties is presented. Then the results of numerical simulations demonstrate various features of the proposed control law. Finally, the paper is completed with some concluding comments.

2. Spacecraft modeling and problem formulation

2.1. Spacecraft attitude dynamics

Consider a rigid space system described by the following attitude kinematics and dynamics equations [28]:

$$\begin{bmatrix} \dot{q}_0 \\ \dot{q} \end{bmatrix} = \frac{1}{2}\begin{bmatrix} -q^T \\ q_0 I + q^{\times} \end{bmatrix}\omega \tag{1}$$

$$J\dot{\omega} = -\omega \times J\omega + u(t) + d(t) \tag{2}$$

where q_0 and q are scalar and vector components of the unit quaternion respectively, with $q = \begin{bmatrix} q_1 & q_2 & q_3 \end{bmatrix}^T \in R^3$ satisfying constraint: $q^T q + q_0^2 = 1$; $\omega = [\omega_1 \omega_2 \omega_3]^T \in R^3$ is the angular velocity vector of body-fixed reference frame of a spacecraft with respect to an inertial reference frame expressed in the body-fixed reference frame; I represents the identity matrix with proper dimensions, and $q^{\times}$ denotes a skew-symmetric matrix, $J \in R^{3\times3}$ is the total inertia matrix of the spacecraft with $J = J^T$, $u(t) = \begin{bmatrix} u_1 & u_2 & u_3 \end{bmatrix}^T \in R^3$ denotes the combined control torque produced by the actuators, and $d(t) = \begin{bmatrix} d_1 & d_2 & d_3 \end{bmatrix}^T \in R^3$ denotes the external disturbance torque vector induced from the environment, which is assumed to be unknown but bounded, i.e., $\|d(t)\| \le \overline{d}$ for a constant $\overline{d}$.

2.2. Control objective

Note that, for some specific applications such as rendezvous of space shuttle with International Space Station and mid-air refueling of an aircraft, the constraints on rigid body angular velocities might be required. Assigned velocity constraints are therefore treated as a set of specifications, which can be stated as follows:

$$\left|\omega_1\right| < k_1, \left|\omega_2\right| < k_2, \left|\omega_3\right| < k_3 \tag{3}$$

for some specified constants $k_i (i = 1, 2, 3)$.

In addition, due to physical limitations on actuators, the actuator control actions generated are limited by certain values, i.e. $\tau(t) \in \Omega := \left\{ \tau \in R^m \middle| \underline{\tau}_i \le \tau_i \le \overline{\tau}_i, \quad i = 1, 2, \cdots, m \right\}$, where $\tau(t)$ is the torque output vector of actuators. For simplicity, we assume that outputs of actuator torques have the same constraint values $(\underline{\tau}, \overline{\tau})$, i.e.

$$\tau(t) \in \Omega := \left\{ \tau \in R^m \middle| \underline{\tau} \le \tau_i \le \overline{\tau}, \quad i = 1, 2, \cdots, m \right\} \tag{4}$$

Note that m actuators are considered and properly mounted along the spacecraft, and the control signals u in Eq. (2) denote the combined control torques produced by the m actuators with proper configuration.

Based on the above statement and assumption, the control objective of this work can be stated as: design a control law for the plant represented by Eqs. (1) and (2) under the constraints represented by Eqs. (3) and (4), such that, for all physically realizable initial conditions, the states of the closed-loop system

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