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Rigid spacecraft attitude control using adaptive integral second order sliding mode

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The aim of this paper is to design a globally robust and globally finite-time convergent attitude controller for a rigid spacecraft. Second order sliding mode control in integral sliding mode is proposed to design the controller. To eliminate the need of advance information about uncertainty and external disturbance bounds, the gains of the proposed controller are calculated using the adaptive laws. The second order sliding mode controller applied is based on geometric homogeneity approach. The finite-time stability is proved by using both the Lyapunov stability and negative homogeneity approach. Simulations are conducted for the attitude tracking and attitude stabilization under the effect of spacecraft mass inertia uncertainty and external disturbances; and the outcomes reveal the effectiveness of the proposed control method.

1. Introduction

Sliding mode control (SMC) is an established robust control method which can be used to address aerospace control problems. The main motivation behind SMC is the inherent robustness and simple control design involved [8,24]. Specifically, the application of SMC to spacecraft attitude control surfaced first in [26]. Since then it is being applied, and variety of controllers have been designed by many researchers [9,13,15,30]; and these controllers have fulfilled the attitude control design purpose to a large extent. In SMC design, the sliding surface is linear combination of system states; hence during the sliding phase, asymptotic convergence is possible, and theoretically infinite time is required to stabilize the states to their equilibrium. In addition to asymptotic convergence, chattering is another shortcoming of SMC.

In attitude control design, in addition to robustness against external disturbances and parametric uncertainties, it is expected from the attitude controller to perform attitude control quickly with good steady precision. Recently, finite-time sliding mode control has proven its competency to satisfy the requirement of quick convergence speed with good steady precision. In control literature, to ensure the finite-time sliding mode, mainly two approaches have been explored, the first is the terminal sliding mode (TSM) [17,27,31], and the second is the higher order sliding mode (HOSM) [10,12]. In TSM and its variants (NTSM, FTSM, NFTSM) [7,29,32,33] based control techniques, the sliding surface chosen is non-linear; so the finite time convergence in the sliding phase is ensured. By using TSM and its variants, significant number of attitude control designs are available in literature [5,6,14]. However, by TSM based control, neither global robustness is ensured (reaching phase still exists) nor chattering is eliminated fully.

HOSM, another advanced version of SMC, primarily works to alleviate the chattering, to ensure the finite time convergence, and to improve the robustness. In HOSM, discontinuous control input is applied on higher time derivatives of the sliding variable; and hence the sliding variable and its higher derivatives converge to zero in finite-time, and simultaneously chattering is also controlled. Through literature survey, it is noticed that HOSM based attitude control design is not common; though, HOSM has proven its usefulness for many non-linear problems. The contribution of HOSM in attitude control design can be seen in [16,19,21,34]. Both in [21,34], firstly, the authors have chosen a linear sliding surface, and then, they have proposed to apply the quasi-continuous higher order sliding mode controller [11]; but, in fact, the linear sliding surface selection gives relative degree $r = 1$, and hence, with the proposed controller the HOSM will not be established [16]. Another drawback with this approach is non-existence of global finite-time convergence, and it is due to the linear sliding surface. Again, in [19], the sliding surface chosen is similar to [21];

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and the super-twisting algorithm based control is applied. Therefore, in the mentioned HOSM attitude control methods [19,21,34], both robustness and finite-time convergence have not been ensured globally.

Integral sliding mode (ISM) control is another extension of SMC, and its performance has been found efficacious to improve the robustness [25]. ISM control actually is the total sliding mode; in which the sliding phase starts from initial time $t_0 = 0$. ISM application for attitude control design is not common, and till date only few research works have been reported [4,20]. In [20], using the control Lyapunov function and the Lyapunov optimizing controller (LOC), respectively, two optimal sliding mode controllers have been designed in integral first order sliding mode to address the tracking control problem. In these, LOC is the finite-time control method; but the main limitation of this method is to select the proper Lyapunov function. In [4], adaptive first order sliding mode control is designed in integral sliding mode to address the attitude tracking problem. However, the global finite-time convergence is not guaranteed; though, the proposed adaptive law to estimate the gain does not show over-adaptation.

In recent years, both the integral terminal sliding mode (ITSM) control [3] and the integral higher order sliding mode (IHOSM) control [18,22,23,35] have shown impressive control performance. The salient features of ITSM control is better robustness and fast response with finite time convergence; however, in terms of chattering alleviation, ITSM performance is same as for TSM or its variants. In IHOSM, characteristics the global robustness, the global finite-time convergence, and chattering alleviation can all be guaranteed together by proper selection of the sliding surface and nominal controller. In [22], using the optimal feedback nominal controller, IHOSM control has been proposed; in fact, it is an open loop control, and calculations are based on the correct initial conditions, but it is quite possible that in practical conditions, initial conditions of states may not be known accurately; therefore the control application will not be easy in uncertain environment. In [35], self-tuning law based IHOSM controller has been designed for a non-linear uncertain system; in this, finite-time controller design is based on geometric homogeneity, but the finite time stability proof is not discussed. More recently, authors of [23] have proposed the IHOSM controller by using quasi-continuous higher order sliding mode control; but the limitation of quasi-continuous mode is remained; though, controller gain calculation is done with adaptive law; and over-adaptation is averted. Additionally, in [18], adaptive IHOSM is applied and two control laws have been proposed to control uncertain system. However, one control law does not ensure finite-time convergence globally; and adaptive law may suffer with over-adaptation. To the best of knowledge, till date the adaptive IHOSM has not been explored for spacecraft attitude control design; and theoretically, an adaptive gain based IHOSM would be the another more appropriate method for attitude control.

Our endeavor is to propose a global robust and global finite-time convergent attitude controller for rigid spacecraft. Firstly, a sliding surface is identified that gives relative degree two. Then, the proposed control method is designed by using the geometric homogeneity controller in integral second order sliding mode (ISSM). To tackle the attitude states's deviation from the sliding surface, the reaching law based control is added with the geometric homogeneity based nominal controller. Additionally, to eliminate the advance requirement of external disturbance and inertia matrix uncertainty upper bounds and to alleviate the chattering, the controller's gains are calculated by using adaptive laws. The rest of the paper is organized as follows. In Section 2, spacecraft attitude dynamics and kinematics are explained. The problem formulation and the proposed control design are discussed in Section 3. The closed-loop stability proof is given in Section 4. In Section 5, simulation results and comparison with existing controllers are reported with extensive discussion. The paper ends with concluding remarks in Section 6.

2. System description

2.1. Mathematical modeling

Quaternion, due to its non-trigonometric expression and non-singularity computation, is the widely used parameter to represent the attitude kinematics of rigid spacecraft [28].

The kinematics equations using the unit quaternion are given as

$$\dot{q}_v = \frac{1}{2}\left(q_4 I_{3\times 3} + q_v^{\times}\right)\omega$$
$$\dot{q}_4 = -\frac{1}{2} q_v^T \omega \tag{1}$$

where $q_v = [q_1\ q_2\ q_3]^T \in \Re^3$ and $q_4 \in \Re$ are the vector and scalar components of the unit quaternion $q = [q_1\ q_2\ q_3\ q_4]^T$, respectively, satisfying the constraint $q_v^T q_v + q_4^2 = 1$, $\omega \in \Re^3$ is the body angular velocity, and $I_{3\times 3}$ is the identity matrix. For any vector $m = [m_1\ m_2\ m_3]^T \in \Re^3$, notation $m^{\times}$ is defined by

$$m^{\times} = \begin{bmatrix} 0 & -m_3 & m_2 \\ m_3 & 0 & -m_1 \\ -m_2 & m_1 & 0 \end{bmatrix}$$

Rigid spacecraft attitude dynamics equation is defined by

$$\dot{\omega} = J^{-1}\left(-\omega^{\times} J\omega + u(t) + d(t)\right) \tag{2}$$

where $J \in \Re^{3\times 3}$ represents the mass inertia matrix with nominal component $J_0 \in \Re^{3\times 3}$ and uncertain term $\delta J \in \Re^{3\times 3}$, $u(t) \in \Re^3$ is the control input, and $d(t) \in \Re^3$ symbolizes the all external disturbances acting on the body.

To define the attitude kinematics and dynamics equation for tracking control problem, the relative attitude error between body frame and a desired reference frame is required to be established. The error quaternion $q_e = [q_{ev}^T, q_{e4}]^T \in \Re^3 \times \Re$ and the angular velocity error $\omega_e \in \Re^3$ are measured from body fixed reference frame to the desired reference frame, and the defining equations are as follows

$$q_{ev} = q_{d4} q_v - q_{dv}^{\times} q_v - q_4 q_{dv}$$
$$q_{e4} = q_{dv}^T q_v + q_4 q_{dv}$$
$$\omega_e = \omega - C\omega_d, \tag{3}$$

where $q_{ev} = [q_{e1}\ q_{e2}\ q_{e3}]^T$ and q_{e4} are the vector and scalar components of the error quaternion, respectively, $q_{dv} = [q_{d1}\ q_{d2}\ q_{d3}]^T \in \Re^3$, $q_{d4} \in \Re$, and $\omega_d = [\omega_{d1}\ \omega_{d2}\ \omega_{d3}]^T \in \Re^3$ are the desired attitude frame vector quaternion, scalar quaternion, and angular velocity, respectively. Both q_e and $q_d = [q_{d1}\ q_{d2}\ q_{d3}\ q_{d4}]^T$ satisfy the constraint $q_{ev}^T q_{ev} + q_{e4}^2 = 1$ and $q_{dv}^T q_{dv} + q_{d4}^2 = 1$, respectively. $C = (q_{e4}^2 - 2q_{ev}^T)I + 2q_{ev}q_{ev}^T - 2q_{e4}q_{ev}^{\times} \in \Re^{3\times 3}$ with $\|C\| = 1$ and $\dot{C} = -\omega^{\times} C$ represents the rotation matrix between body fixed reference frame and desired reference frame.

Then, by using (3), for the attitude tracking case, the kinematics and the dynamics equation could be written as

$$\dot{q}_{ev} = \frac{1}{2}\left(q_{e4} I + q_{ev}^{\times}\right)\omega_e$$
$$\dot{q}_{e4} = -\frac{1}{2} q_{ev}^T \omega_e \tag{4}$$

$$\dot{\omega}_e = J^{-1}\Big(-(\omega_e + C\omega_d)^{\times} J(\omega_e + C\omega_d) + J\left(\omega_e^{\times} C\omega_d - C\dot{\omega}_d\right) + u(t) + d(t)\Big). \tag{5}$$