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Spacecraft Fault Tolerant Attitude Control Design under Control Input Saturation and Uncertainty in Fault Information

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ABSTRACT

In this paper, a continuous stable tracking control algorithm is proposed for spacecraft in the presence of unknown actuator failure, control input saturation and external disturbances. The design method is based on variable structure control and has the following properties: 1) fast and accurate response in the presence of bounded disturbances; 2) robust to the partial loss of actuator effectiveness; 3) explicit consideration of control input saturation. In contrast to traditional fault-tolerant control methods, the proposed controller does not require knowledge of the actuator faults and is implemented without explicit fault detection and isolation processes. In the proposed controller, a single parameter is dynamically adjusted in such a way that it is possible to prove the ultimate boundedness of both attitude and angular velocity errors. The stability proof is based on a Lyapunov direct method and the properties of the singularity free quaternion representation of spacecraft error dynamics. Results of numerical simulations state that the proposed controller is successful in achieving high attitude performance in the presence of external disturbances, actuator multiplicative faults, and control input saturation.

KEYWORDS:

Fault Tolerant Control, Attitude Control, Actuator Multiplicative Fault, Tracking, Variable Structure Control.

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1- Introduction

One of the challenging problems in the field of aerospace engineering is designing a spacecraft attitude tracking controller to maintain stability and performance in the presence of actuator failures, external disturbances and control input saturation. A conventional feedback control design for a complex system may result in an unsatisfactory performance, or even instability, in the event of malfunctions in actuators, sensors or other system components. To overcome such weaknesses, new approaches to control system design have been developed in order to tolerate component malfunctions while maintaining desirable stability and performance properties. These types of control systems are often known as fault-tolerant control systems (FTCS). Generally speaking, FTCS can be classified into two types: passive (PFTCS) and active (AFTCS). In PFTCS, controllers are fixed and are designed to be robust against a class of presumed faults. This approach needs neither fault detection and isolation (FDI) schemes nor controller reconfiguration. Compared to the passive approach, the active FTC (fault-tolerant control) approach requires a FDI mechanism to detect and identify the faults in real time, and then a mechanism to reconfigure the controllers according to the online fault information from the FDI. Compared to the passive approach, the AFTCS needs significantly more computational power to implement [1]. These drawbacks are the motivation to investigate a passive fault-tolerant controller for a spacecraft attitude control system with the occurrence of unexpected faults.

2- Contributions

To achieve high attitude performance, several issues including external disturbances, actuator failures, and control input saturation are required to be explicitly taken into account in the attitude controller design. To address this problem, a fault tolerant attitude tracking controller is proposed for attitude control of spacecraft. Key features of the proposed strategy are that the design of the FTC is independent of the exact information about faults. Also proposed controller is capable of tracking the desired trajectory with explicit consideration of control input constraint and external disturbances. The uniform boundedness of the closed-loop signals is guaranteed by the Lyapunov direct approach and numerical simulations are carried out on the governing nonlinear system equations of motion to show the performance of the proposed controller.

3- Spacecraft Attitude Error Dynamics

Let's assumes the desired motion of the spacecraft is defined by the attitude of a frame (D) whose orientation with respect to (I) is described by the unit quaternion $\mathbf{Q}_d=(q_{0d},\mathbf{q}_d^T)^T \in R\times R^3$ and $\boldsymbol{\omega}_d=(\omega_{d1},\omega_{d2},\omega_{d3})^T$ which denotes the angular velocity of (D) with respect to (I). Now, to address the attitude tracking problem, the attitude tracking error $\mathbf{Q}_e=(q_{0e},\mathbf{q}_e^T)^T$ is defined as the relative orientation between the body frame (B) and the desired frame (D) and it is computed by:

$$\mathbf{q}_e = q_{0_d}\mathbf{q} - q_0\mathbf{q}_d + \mathbf{q}^{\times}\mathbf{q}_d, \tag{1}$$

$$q_{0_e} = q_{0_d}q_0 + \mathbf{q}_d^T\mathbf{q}, \tag{2}$$

The corresponding rotation matrix is given by

$$\mathbf{C}(\mathbf{Q}_e) = (q_{0_e}^2 - \mathbf{q}_e^T\mathbf{q}_e)\mathbf{I}_3 + 2\mathbf{q}_e\mathbf{q}_e^T - 2q_{0_e}\mathbf{q}_e^{\times}, \tag{3}$$

Note that $\|\mathbf{C}\|=1$ and $\dot{\mathbf{C}}=-\boldsymbol{\omega}_e^{\times}\mathbf{C}$, where the relative angular velocity ω_e of (B) with respect to (D) is defined as: $\boldsymbol{\omega}_e=\boldsymbol{\omega}-\mathbf{C}\boldsymbol{\omega}_d$.

Now, the governing differential equations for the attitude tracking error, $\mathbf{q}_e$, when some of its actuators partially fails are stated as follows [2-5]:

$$\dot{q}_{0_e} = -\frac{1}{2}\mathbf{q}_e^T\boldsymbol{\omega}_e = -\frac{1}{2}\boldsymbol{\omega}_e^T\mathbf{q}_e, \tag{4}$$

$$\dot{\mathbf{q}}_e = \frac{1}{2}\left(\mathbf{q}_e^{\times} + q_{0_e}\mathbf{I}_3\right)\boldsymbol{\omega}_e = \frac{1}{2}\left(\left[-\boldsymbol{\omega}_e^{\times} \quad \boldsymbol{\omega}_e\right]\right)\begin{bmatrix}\mathbf{q}_e \\ q_{0_e}\end{bmatrix}, \tag{5}$$

$$\begin{aligned}\mathbf{J}\dot{\boldsymbol{\omega}}_e =& -\left(\boldsymbol{\omega}_e + \mathbf{C}(\mathbf{Q}_e)\boldsymbol{\omega}_d\right)^{\times}\mathbf{J}\left(\boldsymbol{\omega}_e + \mathbf{C}(\mathbf{Q}_e)\boldsymbol{\omega}_d\right) \\ &+ \boldsymbol{\Gamma}\mathbf{u} + \mathbf{J}\left(\boldsymbol{\omega}_e^{\times}\mathbf{C}(\mathbf{Q}_e)\boldsymbol{\omega}_d - \mathbf{C}(\mathbf{Q}_e)\dot{\boldsymbol{\omega}}_d\right),\end{aligned} \tag{6}$$

where $\boldsymbol{\Gamma}=diag\{\Gamma_1, \Gamma_2, \Gamma_3\}$, $0<\Gamma_i\leq 1$ is the actuation effectiveness matrix. The case in which $\Gamma_i=1$ implies that the i[th] actuator is healthy, and $0<\Gamma_i\leq 1$ corresponds to the case in which the ith actuator partially fails.

To ensure robustness of the closed loop system to the partial loose of actuator faults, the following theorem is introduced:

Theorem 1: The control law (8) stabilizes the system described by Equations (4)-(6) in the uniformly ultimately boundedness sense and satisfies the above control objectives

where |.| denotes any vector norm and δ is a positive control constant.

$$u_i = -u_{\max}\left(\frac{s_i}{|s_i| + (k^2+1)\delta}\right), \qquad i = 1,2,3 \tag{7}$$

4- Results

The application of the proposed controller to the attitude control of a spacecraft is presented. It is assumed that each actuator generates a continuous control torque and its output is limited to 5 N.m. Figures (1) to (3) show the results.

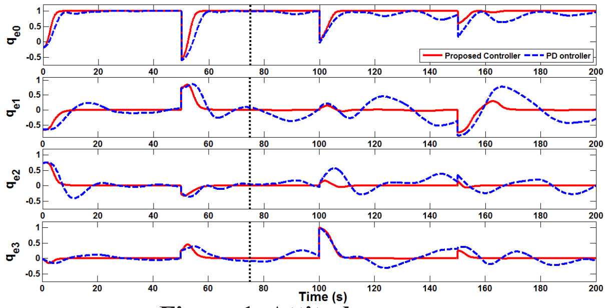

Figure 1. Attitude errors.

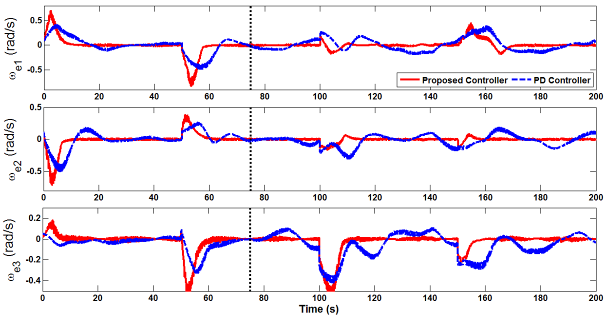

Figure 2. Angular velocity errors.

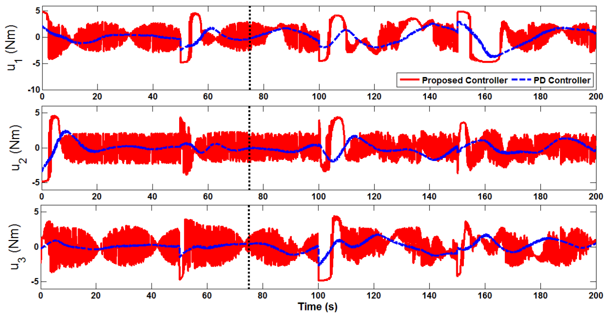

Figure 3. Control efforts

5- Conclusion

An adaptive fault-tolerant attitude tracking control scheme based on variable structure control has been developed for spacecraft attitude stabilization in the presence of input saturation, external disturbances and unknown actuator faults. In contrast to AFTC methods which use an exact FDI process, the proposed method does not require the exact knowledge of the fault information.

The control formulation is based on Lyapunovs direct stability theorem and quaternions properties in the controller synthesis. Evaluating this control scheme using numerical simulations, shows that the proposed fault-tolerant attitude controller is able to recover from actuator failure and to achieve high precision tracking. Furthermore, the control objective can be achieved even under actuator input constraints.

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