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Iterative Learning Observer-based Sliding Mode Fault-Tolerant Control of a Rigid-Flexible System with External Disturbances

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Abstract

The paper discusses the design of an observer-based fault-tolerant control (FTC) algorithm and active vibration control for stabilizing a flexible spacecraft's attitude subject to external disturbances. An iterative learning observer was developed in order to estimate the torque deviation caused by actuator faults. One of the main features of the proposed observer is the consideration of external disturbances in its structure. Next, a fault-tolerant sliding mode control (SMC) law based on a proportional-integral-derivative (PID) structure with a time-varying switching gain is proposed to generate control signals with ideal performance. To minimize residual vibrations during and after the maneuver, the strain rate feedback (SRF) control algorithm is also activated simultaneously with fault-tolerant control. By using Lyapunov theory, the proposed control strategies guarantee global stability for the closed loop system. Numerical simulations as a comparative study have been used to demonstrate the effectiveness of the developed system compared to conventional algorithms, such as integral sliding mode control, when handling actuator failures, external disturbances, and flexible body excitations in rigid-flexible dynamic systems.

Keywords: fault tolerant control; sliding mode; strain rate feedback; iterative learning observer.

1. Introduction

Attitude control systems have played a crucial role in advanced space missions, particularly in the presence of environmental disturbances and uncertainty. As well as numerous efforts to improve spacecraft attitude control system reliability, numerous uncertainties arise in the actuators within this subsystem. There is a possibility that these uncertainties may result in a malfunctioning control system, resulting in the loss of the mission and the associated economic and safety risks. Also, the flexible nature of the system leads to disturbances and uncertainty, especially when the actuators fail [1].

There have been a variety of control techniques implemented over the past few decades. In comparison to other control approaches, sliding mode control is simple, robust to external disturbances, and system parameter changes. Integral sliding mode control is structured such that the reaching phase of the sliding surface is eliminated from the very beginning of the maneuver, thereby ensuring robustness [2]. Particularly, SMCs based on PID algorithms offer all the advantages discussed above, such as fast response time, reduced sensitivity to parameter changes, and external/internal disturbances [3].

Alternatively, the spacecraft can be equipped with a FTC system that compensates for the actuator fault. Active FTC requires fault detection and isolation mechanisms, unlike passive FTC, which deals with online fault compensation. As a result, determining fault information, which has been proposed in several approaches, plays a significant role in designing active FTC systems. A wide range of systems use observers as fault estimators due to their ease of implementation [4].

Vibrations caused by flexible parts can threaten systems with rigid-flexible dynamics. Strain rate feedback is simple to implement and also offers a large active damping area and the capability of stabilizing multiple vibration modes [5].

The article discusses the development of a control approach that combines a nominal PID SMC with a fault-tolerant algorithm that incorporates a time-varying switching gain, as well as an AVC method. Furthermore, an iterative learning observer that includes external disturbances and sign functions is proposed for estimating actuator faults.

2. Dynamic modelling and controller design

A flexible spacecraft dynamic with a rigid hub and two flexible panels equipped with PZT sensors/actuators is described as [6]:

$$\begin{bmatrix}\mathbf{M}_{\mathrm{R}} & \mathbf{M}_{\mathrm{RF}}\\ \mathbf{M}_{\mathrm{FR}} & \mathbf{M}_{\mathrm{F}}\end{bmatrix}\begin{bmatrix}\dot{\boldsymbol{\omega}}\\ \ddot{\boldsymbol{\eta}}_{\mathrm{k}}\end{bmatrix}+\begin{bmatrix}\mathbf{C}_{\mathrm{R}} & \mathbf{C}_{\mathrm{RF}}\\ \mathbf{C}_{\mathrm{FR}} & \mathbf{C}_{\mathrm{F}}\end{bmatrix}\begin{bmatrix}\boldsymbol{\omega}\\ \dot{\boldsymbol{\eta}}_{\mathrm{k}}\end{bmatrix} + \begin{bmatrix}\mathbf{0} & \mathbf{0}\\ \mathbf{0} & \mathbf{K}_{\mathrm{F}}\end{bmatrix}\begin{bmatrix}\boldsymbol{\Phi}\\ \boldsymbol{\eta}_{\mathrm{k}}\end{bmatrix}=\begin{bmatrix}\mathbf{u}\\ -\mathbf{P}^{\mathrm{T}}\mathrm{g}\mathbf{A}_{\mathrm{P}}^{\mathrm{a}}\end{bmatrix} \quad (1)$$

$$\mathbf{A}_{\mathrm{P}}^{\mathrm{a}}=\mathrm{g}\mathbf{N}^{-1}\mathbf{P}^{\mathrm{T}}\boldsymbol{\eta}_{\mathrm{P}}^{\mathrm{s}}$$

where $\mathbf{u}$, $\boldsymbol{\eta}_{\mathrm{k}}$ and g denote control torque, the k$^{\mathrm{th}}$ generalized coordinates, and PZT sensor/actuator gain amplifier, respectively. The $\mathbf{M}$, $\mathbf{C}$, $\mathbf{K}$, $\mathbf{A}$, $\mathbf{N}$, and $\mathbf{P}$ are represent the mass, damping, stiffness matrices, and the parameters related to PZT patches that can be decomposed in sensor and actuator parts corresponding to the sensor/actuator voltages $\mathbf{A}_P^s$ and $\mathbf{A}_P^a$, respectively. The subscripts *R* and *F* represent the rigid and flexible dynamic parts, and superscripts *a* and *s* denote sensor and actuator, respectively.

The actuator fault can be modeled as follows:

$$\mathbf{u}_{\mathrm{c}}=\mathbf{E}(\mathrm{t})\mathbf{u}_{\mathrm{h}}=\mathbf{u}_{\mathrm{h}}+(\mathbf{E}(\mathrm{t})-\mathbf{I}_{3\times 3})\mathbf{u}_{\mathrm{h}} = \mathbf{u}_{\mathrm{h}}+\mathbf{u}_{\mathrm{f}} \quad (2)$$

where $\mathbf{E}(t)=diag\{e_1(t)\,.\,e_2(t)\,.\,e_3(t)\}$ denotes the reducing effectiveness matrix of spacecraft actuator faults with $0\le \mathbf{e}_i(t)\le 1$ $(i=1.2.3)$, $\mathbf{u}_{\mathrm{h}}$ and $\mathbf{u}_{\mathrm{f}}$ are the healthy control torque and the torque deviation caused by the actuator faults, respectively.

Figure 1 shows a PID-based sliding mode fault-tolerant control, followed by an iterative learning observer, and an active vibration control algorithm.

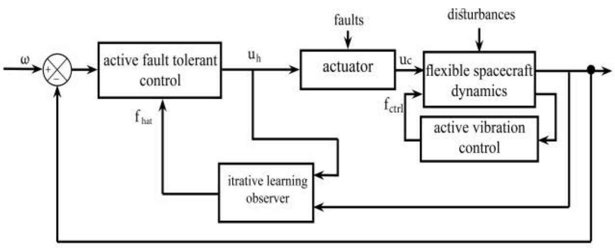

Figure 1. Block diagram of the system

In order to estimate faults, the following fault estimation observer is designed:

$$\begin{aligned}\mathbf{M}_{\mathrm{R}}\dot{\hat{\boldsymbol{\omega}}}&=-\mathbf{M}_{\mathrm{RF}}\ddot{\boldsymbol{\eta}}_{\mathrm{k}}-\mathbf{C}_{\mathrm{R}}\hat{\boldsymbol{\omega}}-\mathbf{C}_{\mathrm{RF}}\dot{\boldsymbol{\eta}}_{\mathrm{k}}+\mathbf{u}_{\mathrm{h}}\\&\quad+\hat{\mathbf{u}}_{\mathrm{f}}(\mathrm{t})+\lambda_1(\boldsymbol{\omega}-\hat{\boldsymbol{\omega}})+\boldsymbol{\lambda}_2 sgn(\boldsymbol{\omega}-\hat{\boldsymbol{\omega}})\\ \hat{\mathbf{u}}_{\mathrm{f}}(\mathrm{t})&=\mathbf{K}_1\hat{\mathbf{u}}_{\mathrm{f}}(t-\tau)+\mathbf{K}_2 sgn(\boldsymbol{\omega}-\hat{\boldsymbol{\omega}})\end{aligned} \quad (3)$$

where $(\,\hat{}\,)$ represents the estimation of the parameter. τ is the updating interval, λ_1 is a positive scalar parameter, $\boldsymbol{\lambda}_2$ is a positive definite matrix depends on the upper bound of disturbance, $\mathbf{K}_1$ and $\mathbf{K}_2$ are positive definite gain matrixes, respectively. Angular velocities and quaternions are used to develop SMC:

$$\mathbf{S}=\boldsymbol{\omega}+k\mathbf{q}_{1:3} \quad (4)$$

where k is a positive constant.

According to the equations of motion of the system and the sliding surface, the equivalent control can be written as:

$$\begin{aligned}\mathbf{u}_{\mathrm{eq}}&=\mathbf{M}_{\mathrm{RF}}\ddot{\boldsymbol{\eta}}_{\mathrm{k}}+\mathbf{C}_{\mathrm{R}}\boldsymbol{\omega}+\mathbf{C}_{\mathrm{RF}}\dot{\boldsymbol{\eta}}_{\mathrm{k}}\\&\quad-0.5k\mathbf{M}_{\mathrm{R}}(q_0\boldsymbol{\omega}+\mathbf{q}_{1:3}^{\times}\boldsymbol{\omega})\end{aligned} \quad (5)$$

Additionally, nominal control is suggested as follows:

$$\begin{aligned}\mathbf{u}_{\mathrm{nom}}&=\mathbf{u}_{\mathrm{eq}}-K_P\mathbf{q}_{1:3}-K_d\tanh\left(\frac{\boldsymbol{\omega}}{p^2}\right)\\&\quad-K_i\int\mathbf{q}_{1:3}\,dt\end{aligned} \quad (6)$$

where K_P, K_d, and K_i are positive constants, and p^2 is a non-zero sharpness function.

The proposed sliding mode based fault-tolerant controller is presented as follows:

$$\mathbf{u}_c=\mathbf{u}_{\mathrm{nom}}+\mathbf{u}_{\mathrm{FTC}} \quad (7)$$

Therefore, the $\mathbf{u}_{\mathrm{FTC}}$ control rule is selected as follows:

$$\begin{aligned}&\mathbf{u}_{\mathrm{FTC}}=\\&\begin{cases}-\mathbf{K}_s\mathbf{S}-\beta(t)\dfrac{(\mathbf{S}^T\mathbf{M}_{\mathrm{R}}^{-1})^{\mathrm{T}}}{\|(\mathbf{S}^T\mathbf{M}_{\mathrm{R}}^{-1})^{\mathrm{T}}\|} & \text{if } \mathbf{S}\neq\mathbf{0}\\ \mathbf{0} & otherwise\end{cases}\\&\beta(t)=\frac{\sqrt{3}e_m\|\mathbf{u}_{\mathrm{nom}}\|_\infty+d_M+\varepsilon}{1-e_m}\end{aligned} \quad (8)$$

where ε, K_s, and $\beta(t)$ are positive constants and time variable gain, respectively.

PZT patches are used to control vibration for high-precision maneuvers. PZT sensors' output voltage can be expressed as follows:

$$\begin{aligned}V_s(t)&=G_Ci(t)=G_Ce_{31}\left(\frac{h_b}{2}\right.\\&\quad\left.+h_{\mathrm{P}}\right)z_P\int_0^{\mathrm{L_P}}\frac{\partial^2}{\partial \mathrm{x}^2}\boldsymbol{\psi}^{\mathrm{k}}(\mathrm{x})\dot{\boldsymbol{\eta}}_{\mathbf{k}}(\mathrm{t})\mathrm{dx}\end{aligned} \quad (9)$$

where $i(t)$, e_{31} and $\boldsymbol{\psi}^k(x)$ are PZT circuit current, voltage constant and the element shape functions, respectively. Moreover, G_C, z_P, h_P, and L_P are constant gain, width, length and thickness of PZTs, respectively. The input voltage to the actuator $\mathbf{V}_a$ is given by:

$$\mathbf{V}_\mathrm{a} = \mathbf{K}_\mathrm{pzt} V_s(\mathrm{t}) \tag{10}$$

where $\boldsymbol{K}_{pzt}$ is the controller gain matrix.

3. Results and Discussion

This section presents numerical simulations for flexible spacecraft systems to illustrate the performance of the proposed controller. The fault-tolerant SMC parameters are selected as: $K_d = 0.5$, $K_p = 0.5$ and $K_i = 0.0001$, sharpness parameters $P^2 = 0.1$, fault-tolerant control gains $K_s = 0.0001$, and $\varepsilon = 0.01$. Also, for implementation of the AVC algorithm, design parameters are considered to be: $G_C = 127$ and $\mathbf{K}_{PZT} = [32 \quad 27 \quad 19 \quad 7]$.

The performance of the proposed observer and control laws is shown in Figs 2-4. Figure 2 illustrates that the SMC algorithm without FTC torque requires more control effort especially at the beginning of the maneuver. Furthermore, the fault-tolerant algorithm reduces the initial torque requirement and results in smoother control signals. As well, the observer can diagnose the fault as soon as the maneuver begins.

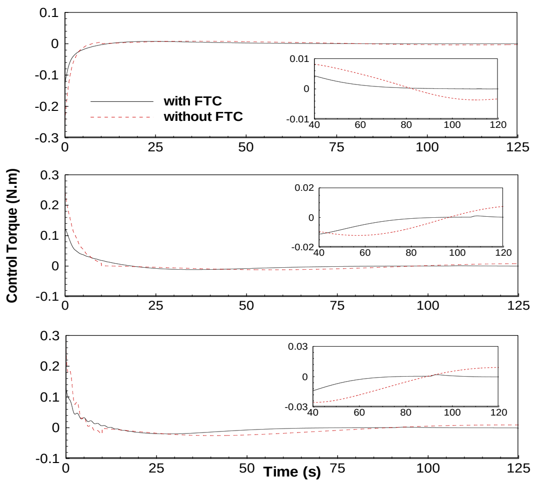

Figure 2. time history of the control torque

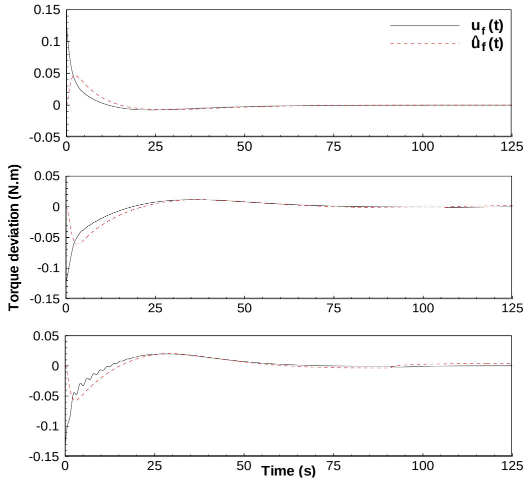

Figure 3. Control torque deviation caused by actuator fault

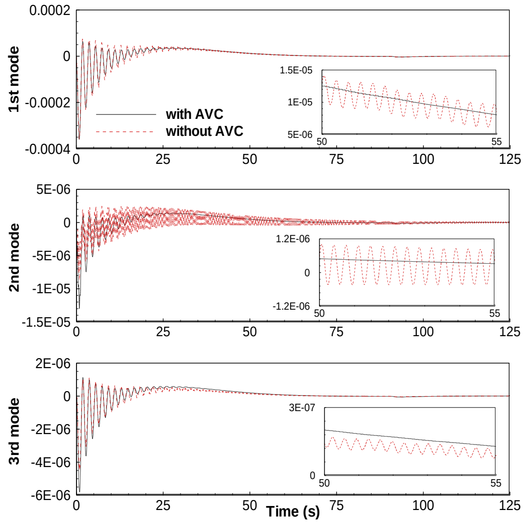

Figure 4. The first three vibration mode with FTC

The control torque deviation caused by actuator faults is illustrated in Fig. 3 as well as the optimal performance of the proposed observer. As can be seen, a torque loss is detected in the first five seconds of the maneuver, and after 25 seconds, the system converges. As can be seen in Fig. 4, it can be demonstrated that the strain rate feedback algorithm controls the vibrations of the system during and after maneuvers. The algorithm enhances the attitude control system's performance by reducing oscillations at the beginning of the maneuver and eliminating vibrations at the end.

4. Conclusions

In this paper, strain rate feedback and sliding mode fault-tolerant algorithms are applied to control vibrations and three-axis maneuver of a flexible spacecraft simultaneously. The system is perturbed by external disturbances and a time-varying actuator fault. An iterative learning observer is presented to estimate torque deviation caused by actuator faults, ensuring fast convergence and high accuracy. Lyapunov's theorem guarantees global stability in the presence of external disturbances and time-varying actuator faults. Noteworthy is the fact that the proposed FTC algorithm has been shown to accommodate external disturbances, actuator failures and flexible parts vibrations.

5. References

[1] C. Liu, G. Vukovich, Z. Sun, and K. Shi, "Observer-based fault-tolerant attitude control for spacecraft with input delay," *Journal of Guidance, Control, and Dynamics*, vol. 41, no. 9, pp. 2041-2053, 2018.

[2] C. Liu, G. Wen, Z. Zhao, and R. Sedaghati, "Neural-network-based sliding-mode control of an uncertain robot using dynamic model approximated switching gain," *IEEE transactions on cybernetics*, vol. 51, no. 5, pp. 2339-2346, 2020.

[3] M. N. Duc, T. N. Trong, and Y. S. Xuan, "The quadrotor MAV system using PID control," in *2015 IEEE International Conference on Mechatronics and Automation (ICMA)*, 2015: IEEE, pp. 506-510.

[4] E. Bernardi and E. J. Adam, "Observer-based fault detection and diagnosis strategy for industrial processes," *Journal of the Franklin Institute,* vol. 357, no. 14, pp. 10054-10081, 2020.

[5] M. Shahravi and M. Azimi, "A hybrid scheme of synthesized sliding mode/strain rate feedback control design for flexible spacecraft attitude maneuver using time scale decomposition," *International Journal of structural Stability and dynamics*, vol. 16, no. 02, p. 1450101, 2016.

[6] M. Shahravi and M. Azimi, "A comparative study for collocated and non-collocated sensor/actuator placement in vibration control of a maneuvering flexible satellite," *Proceedings of the institution of Mechanical Engineers, Part C: Journal of mechanical engineering science,* vol. 229, no. 8, pp. 1415-1424, 2015.