PAPER • OPEN ACCESS

Adaptive Backstepping Sliding Mode Fault Tolerant Control for Satellite Attitude under Actuator Faults

To cite this article: Junhai Huo *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **608** 012040

IOP Conf. Series: Materials Science and Engineering **608** (2019) 012040 doi:10.1088/1757-899X/608/1/012040

Adaptive Backstepping Sliding Mode Fault Tolerant Control for Satellite Attitude under Actuator Faults

Junhai Huo[1], Tao Meng[1,*] and Zhonghe Jin[1]

[1]School of Aeronautics and Astronautics, Zhejiang University, Hangzhou, 310027, China

[*]Corresponding author: mengtao@zju.edu.cn

Abstract. Modern spacecraft missions place stringent performance requirements on the reliability and stability of spacecraft attitude control system. However, during long-term in-orbit mission, actuators may suffer faults. In this paper, we proposed an adaptive fault tolerant control law for attitude control under actuator failures and external disturbances. Firstly, the attitude dynamic model under actuator faults and attitude kinematics are described. Then, in order to solve the attitude control problem under actuator faults and external disturbances, an adaptive backstepping sliding mode fault tolerant control scheme is designed. According to Lyapunov theory, the closed-loop system is proved to be globally asymptotically stable. Finally, the numerical simulation results demonstrate that the proposed adaptive controller can achieve anticipative attitude control performance, fault information estimation and well fault-tolerant capability.

1. Introduction

The growing development of different space exploration missions has motivated significant demands for the reliable and autonomous control of spacecraft. Attitude control system (ACS), as one of spacecraft's subsystems, plays a valuable role in guaranteeing the success of space missions. During the past decades, far-ranging efforts have been devoted to this issue, and a large amount of modern control techniques are documented in the literature [1-5]. However, most of these existing methods focus on spacecraft with healthy actuators. During the long-term in-orbit mission, the possibility of malfunction in actuator increases due to spacecraft's challenging operating conditions. Once the anomaly do occur, there would be huge economy loss. Hence, how to guarantee the reliability and safety of the controlled plants has become a serious problem to be solved.

Generally speaking, the existing fault tolerant control (FTC) methods can be divided into two parts: passive FTC and active FTC. The passive FTC [6, 7] is based on the robust technique and implemented as a fixed controller. However, the passive FTC only tolerates a limited number of faults, and it achieves robustness at the cost of decreased nominal performance. In contrast, active FTC solves the fault control problem by adjusting and modifying the controller based on real-time fault detection, identification and controller reconfiguration so that the stability of system and well control performance can be maintained. Taking advantage of greater performance and ability to handle a wider range of failure, the active FTC has motivated more significant research during the past years, such as multiple model [8], feedback linearization [9], sliding mode control [10], adaptive control [11, 12], control allocation [13, 14], eigenstructure assignment [15], model predictive control[16, 17], etc. However, most satellite attitude fault tolerant control methods can only deal with a single type of actuator fault. For example, [10, 11] can only deal with partial failure of actuator. Therefore, the fault tolerance of these control methods is very limited. On the other hand, spacecraft in-orbit will inevitably be affected by external disturbances such as gravity gradient moment, aerodynamic moment, etc. This problem will limit the practical application of the existing attitude fault tolerant control methods. External disturbance and actuator fault are two key problems which affect the performance of fault tolerant controller. For this reason, how to design attitude fault tolerant controller to realize reliable and stable control under the condition of multi-type failure of actuator and external disturbance has become an urgent problem to be solved.

In this paper, we concentrate on the design of an active fault tolerant control algorithm for spacecraft attitude under multiple faults and external disturbances. Based on the backstepping control algorithm, the sliding mode was introduced because of its strong robustness. The system change caused by fault can be regarded as an uncertainty, and this uncertainty can be estimated by adaptive algorithm and used for controller design. Simulation results illustrate the well performance of the adaptive backstepping sliding mode fault tolerant controller.

The rest of this paper is organized as follows. Section 2 is devoted to describe the attitude kinematics and attitude dynamics with unknown actuator faults. In Section 3, an adaptive fault tolerant controller is proposed and closed-loop system stability analysis is derived. The effectiveness and superiority of the control scheme are verified by numerical simulation in Section 4. Finally, the conclusion of this paper is shown in Section 5.

2 Dynamics model

2.1 Attitude dynamics

The satellite attitude dynamics is

$$\boldsymbol{J}\dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times \boldsymbol{J}\boldsymbol{\omega} = \boldsymbol{u_c} + \boldsymbol{d} \tag{1}$$

where $\boldsymbol{J}$ denotes the inertia matrix of the satellite; $\boldsymbol{\omega}$ is the satellite attitude velocity; $\boldsymbol{u_c}$ is the control torque; $\boldsymbol{d}$ is the external disturbance torque.

For a healthy-actuator system, the actual output can accurately respond to the command input, $\boldsymbol{u} = \boldsymbol{u_c}$. However, actuator faults are usually inevitable. These faults include: 1) Partial loss of energy: actuator can only respond partially to the expected control command; 2) Continuous float: actuator cannot output the expected actuating power accurately, and there exists a small bias; 3) Complete loss of energy: actuator completely fails to work; 4) Locking: actuator has a fixed and uncontrolled output. In this study, loss of effectiveness fault and bias fault are considered. The faults can be modeled as

$$\boldsymbol{u} = \boldsymbol{e}\boldsymbol{u_c} + \boldsymbol{f} \tag{2}$$

where $\boldsymbol{u_c} = [u_{c1}, u_{c2}, u_{c3}]$ is the command torque input of actuators; $\boldsymbol{e} = \text{diag}([e_1, e_2, e_3])$ represents the effectiveness matrix of actuator; $\boldsymbol{f} = [f_1, f_2, f_3]$ denotes the bias fault. Ultimately, the fault satellite attitude dynamics model can be written as

$$\boldsymbol{J}\dot{\boldsymbol{\omega}} + \boldsymbol{\omega} \times \boldsymbol{J}\boldsymbol{\omega} = (\boldsymbol{e}\boldsymbol{u_c} + \boldsymbol{f}) + \boldsymbol{d} \tag{3}$$

2.2 Attitude kinematics

The satellite attitude kinematics employing quaternion can be written as

$$\dot{\boldsymbol{q}}_{\boldsymbol{v}} = \frac{\boldsymbol{1}}{\boldsymbol{2}}(\boldsymbol{q_0}\boldsymbol{I_3} + \boldsymbol{S}(\boldsymbol{q_v}))\boldsymbol{\omega} \tag{4}$$

$$\boldsymbol{q_0} = -\frac{\boldsymbol{1}}{\boldsymbol{2}}\boldsymbol{q}_{\boldsymbol{v}}^{\boldsymbol{T}}\boldsymbol{\omega} \tag{5}$$

IOP Conf. Series: Materials Science and Engineering **608** (2019) 012040 doi:10.1088/1757-899X/608/1/012040

where $\boldsymbol{q} = [\boldsymbol{q_v}, q_0]$ is the unit quaternion; $\boldsymbol{I_3}$ is an identity matrix; $\boldsymbol{S}(\cdot)$ means the skew-symmetric matrix as follows:

$$\boldsymbol{S}(\boldsymbol{x}) = \begin{bmatrix} \mathbf{0} & -x_3 & x_2 \\ x_3 & \mathbf{0} & -x_1 \\ -x_2 & x_1 & \mathbf{0} \end{bmatrix}$$

Define the error quaternion $\boldsymbol{q_e} = [\boldsymbol{q_{ev}}, q_{e0}]$ as the maneuvering quaternion from the initial quaternion $\boldsymbol{q}$ to the desired quaternion $\boldsymbol{q_d} = [\boldsymbol{q_{dv}}, q_{d0}]$, then we have

$$\boldsymbol{q_e} = \boldsymbol{q_d} \otimes \boldsymbol{q} \tag{6}$$

where $\otimes$ is quaternion product. The error angular velocity $\boldsymbol{\omega_e}$ is written as

$$\boldsymbol{\omega_e} = \boldsymbol{\omega} - \boldsymbol{\omega_d} \tag{7}$$

where $\boldsymbol{\omega}$ is the initial angular velocity; $\boldsymbol{\omega_d}$ is the desired angular velocity. Substituting Eq.6 and Eq.7 into Eq.4 and Eq.5, and the error quaternion kinematics can be derived as

$$\dot{q}_{ev} = \frac{1}{2}(q_{e0}\boldsymbol{I_3} + \boldsymbol{S}(\boldsymbol{q_{ev}}))\boldsymbol{\omega_e} \tag{8}$$

$$q_{e0} = -\frac{1}{2}q_{ev}^T\boldsymbol{\omega_e} \tag{9}$$

3 Fault tolerant controller design

In this section, the adaptive backstepping sliding mode fault tolerant controller is proposed to deal with the attitude control problem under the actuator faults and external disturbances.

The first-order backstepping variable is

$$\boldsymbol{z_1} = [\boldsymbol{q_{ev}}; \mathbf{1} - \boldsymbol{q_{e0}}] \tag{10}$$

The second-order virtual backstepping variable is

$$\boldsymbol{z_2} = \boldsymbol{\omega_e} - \boldsymbol{\sigma} \tag{11}$$

Then the time derivative of $\boldsymbol{z_1}$ is

$$\begin{aligned} \dot{z}_1 &= \frac{1}{2}\begin{bmatrix} q_{e0}\boldsymbol{I_3} + \boldsymbol{S}(\boldsymbol{q_{ev}}) \\ sgn(q_{e0})q_{ev}^T \end{bmatrix}\boldsymbol{\omega_e} \\ &= \frac{1}{2}\boldsymbol{Q}^T(z_2 + \boldsymbol{\sigma}) \end{aligned} \tag{12}$$

where $\mathbf{Q} = \begin{bmatrix} q_{e0}\boldsymbol{I_3} + \boldsymbol{S}(\boldsymbol{q_{ev}}) \\ \mathrm{sgn}(q_{e0})\boldsymbol{q_{ev}^T} \end{bmatrix}^T$, $\boldsymbol{\sigma}$ is a virtual variable that need to be chosen.

Firstly, we define a Lyapunov function as

$$\boldsymbol{V_1} = \boldsymbol{z_1^T z_1} \tag{13}$$

$$\dot{\boldsymbol{V}}_1 = 2\boldsymbol{z_1^T}\dot{\boldsymbol{z}}_1 = \boldsymbol{z_1^T Q^T}(\boldsymbol{z_2} + \boldsymbol{\sigma}) \tag{14}$$

Thus, the virtual variable is chosen as $\boldsymbol{\sigma} = -\boldsymbol{k_1 Q z_1}$, where $\boldsymbol{k_1}$ is a diagonal gain matrix. Then we have

$$\dot{\boldsymbol{V}}_1 = -\boldsymbol{z_1^T Q^T k_1 Q z_1} + \boldsymbol{z_1^T Q^T z_2} \tag{15}$$

Secondly, differentiating Eq.11, we have

$$\dot{z}_2 = \dot{\omega}_e - \dot{\sigma} \tag{16}$$

Combining Eq.3, Eq.7 and Eq.16, we have

$$J\dot{z}_2 = J\dot{\omega}_e - J\dot{\sigma} = -\omega \times J\omega + Eu_c + F + d - J\dot{\omega}_d - J\dot{\sigma} \tag{17}$$

Then the second Lyapunov function can be defined as

$$V_2 = V_1 + \frac{1}{2} z_2^T J z_2 \tag{18}$$

Differentiating Eq.18, we get

$$\dot{V}_2 = \dot{V}_1 + z_2^T J \dot{z}_2 \tag{19}$$

Define the sliding mode surface as

$$s = z_2 \tag{20}$$

Substituting Eq.17 and Eq.20, we get

$$\dot{V}_2 = \dot{V}_1 + s^T(-\omega \times J\omega + eu_c + F + d - J\dot{\omega}_d - J\dot{\sigma}) \tag{21}$$

There exists shaking in the sliding mode control, and it can be weakened by introducing the approach law. In order to guarantee system robustness and reduce the shaking caused by external disturbances, the exponential approach law $s = -\varepsilon \mathrm{sgn}(s) - k_2 s$ is adopted in this paper.
In order to make $\dot{V}_2 \leq 0$, the controller can be designed as follows

$$u_c = (-\varepsilon sgn(s) - k_2 s + \omega \times J\omega - \hat{F} + J\dot{\omega}_d + J\dot{\sigma} - Qz_1)/\hat{E} \tag{22}$$

where $\hat{F}$ and $\hat{E}$ are the estimation of E and F, respectively. We define the estimation error as e_E and e_F, and thus we have

$$e_E = E - \hat{E} \tag{23}$$

$$e_F = F - \hat{F} \tag{24}$$

Substituting the proposed controller Eq.22 into Eq.21, and combining Eq.23 and Eq.24, after some simplification, we get

$$\dot{V}_2 = -z_1^T Q^T k_1 Q z_1 + s^T(-\varepsilon sgn(s) - k_2 s + e_E u_c - \hat{F} + F + d) \tag{25}$$

Define the following Lyapunov function

$$V_3 = V_2 + \frac{e_F^2}{2\gamma} + \frac{e_E^2}{2\lambda} \tag{26}$$

Differentiating Eq.26, we get

$$\begin{aligned} \dot{V}_3 &= \dot{V}_2 - \frac{e_F \dot{\hat{F}}}{\gamma} - \frac{e_E \dot{\hat{E}}}{\lambda} \\ &= -z_1^T Q^T k_1 Q z_1 + s^T(-\varepsilon sgn(s) - k_2 s + e_E u_c - \hat{F} + F + d) - \frac{e_F \dot{\hat{F}}}{\gamma} - \frac{e_E \dot{\hat{E}}}{\lambda} \end{aligned}$$

$$= -\boldsymbol{z_1^T Q^T k_1 Q z_1} + \boldsymbol{s^T}(-\boldsymbol{\varepsilon sgn(s)} - \boldsymbol{k_2 s} + \boldsymbol{d}) + \boldsymbol{e_E}\left(\boldsymbol{s^T u_c} - \frac{\dot{\widehat{\boldsymbol{E}}}}{\boldsymbol{\lambda}}\right) + \boldsymbol{e_F}\left(\boldsymbol{s^T} - \frac{\dot{\widehat{\boldsymbol{F}}}}{\boldsymbol{\gamma}}\right)$$

The adaptive laws of $\widehat{\boldsymbol{E}}$ and $\widehat{\boldsymbol{F}}$ are designed as

$$\dot{\widehat{\boldsymbol{E}}} = \boldsymbol{\lambda s^T u_c} \tag{27}$$

$$\dot{\widehat{\boldsymbol{F}}} = \boldsymbol{\gamma s^T} \tag{28}$$

If $\boldsymbol{\varepsilon}$ satisfies

$$\|\boldsymbol{d}\| < \boldsymbol{\varepsilon}$$

Ultimately, the derivative of Lyapunov function $\boldsymbol{V_3}$ is

$$\dot{\boldsymbol{V}}_3 = -\boldsymbol{z_1^T Q^T k_1 Q z_1} + \boldsymbol{s^T}(-\boldsymbol{\varepsilon sgn(s)} - \boldsymbol{k_2 s} + \boldsymbol{d})$$
$$\leq -\boldsymbol{z_1^T Q^T k_1 Q z_1} - \boldsymbol{s^T k_2 s} \leq \boldsymbol{0}$$

4 Simulation

In this section, numerical simulations are conducted to evaluate the performance of the proposed fault tolerant attitude controller. The objective of the simulation is to maintain the stable attitude under the condition of actuator faults and external disturbances. The moment of inertia of satellite is given as $J = \mathrm{diag}[1.08, 1.08, 1.08]\mathrm{kgm}^2$; the initial satellite attitude angle is [3; 3; 3]°; the initial angular velocity is [0.1; 0.1; 0.1]°/s; the desired attitude angle and angular velocity are [0; 0; 0]° and [0; 0; 0]°/s, respectively. Because of the periodicity of orbital disturbances, we randomly suppose the external disturbance torque to be

$$\boldsymbol{d} = \begin{bmatrix} \boldsymbol{d_x} \\ \boldsymbol{d_y} \\ \boldsymbol{d_z} \end{bmatrix} = \begin{bmatrix} \boldsymbol{2e^{-5} * cos(pi * t) + 1e^{-5}} \\ \boldsymbol{1e^{-5} * cos(pi * t) + 2e^{-5}} \\ \boldsymbol{3e^{-5} * sin(pi * t) - 1e^{-5}} \end{bmatrix}$$

The controller parameters are chosen as $k_1 = \mathrm{diag}[0.005, 0.005, 0.005]$; $k_2 = \mathrm{diag}[0.04, 0.04, 0.04]$; $\lambda = 2000$; $\gamma = 0.001$; $\varepsilon = 5 \times 10^{-5}$; the actuators partial loss of effectiveness matrix is chosen as $\boldsymbol{e} = \mathrm{diag}([1, 0.5, 1])$; the bias fault matrix is $\boldsymbol{f} = [0, 0, 1 \times 10^{-5}]\mathrm{Nm}$.

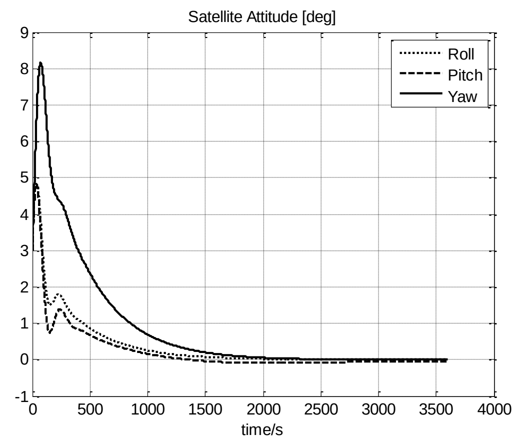

Figure 1. Satellite attitude

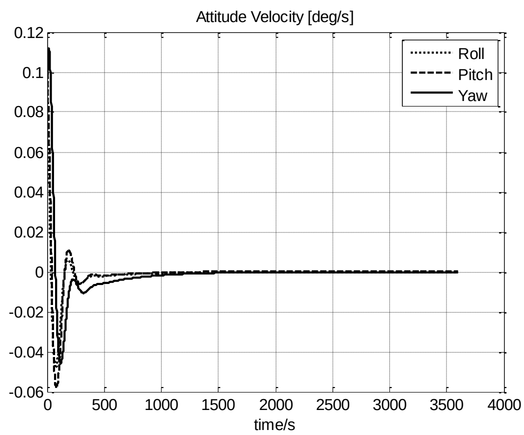

Figure 2. Satellite attitude velocity

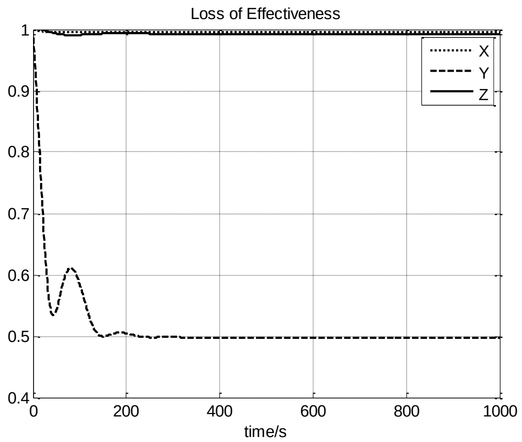

Figure 3. Estimation of loss of effectiveness

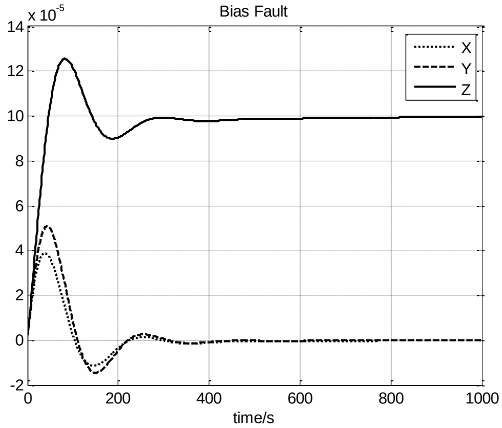

Figure 4. Estimation of bias fault

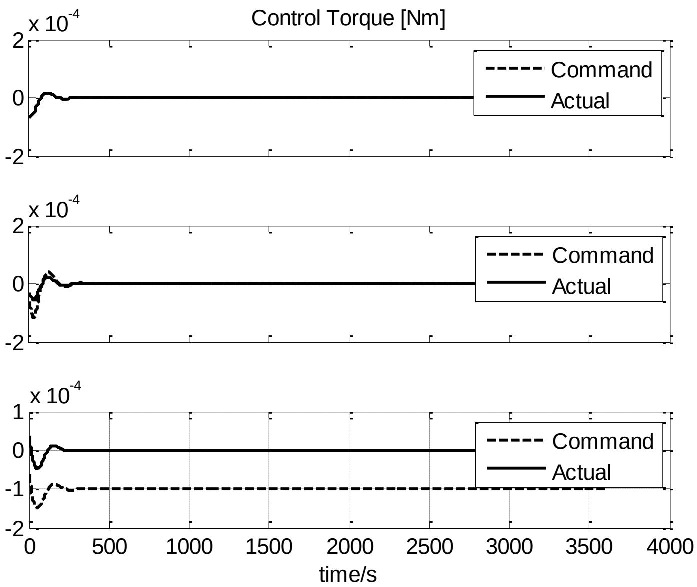

Figure 5. Control torque (command and actual)

Applying the controller Eq.22 and adaptive update laws Eq.27 and Eq.28, the simulation results are illustrated as Fig.1-5. The time responses of the attitude and attitude velocity are presented in Fig.1-2. The satellite attitude and attitude velocity converge to zero asymptotically under the adaptive fault tolerant controller. Evolution of the estimations of actuator faults are displayed by Fig.3-4. It can be seen that the estimated loss of effectiveness and bias fault are both bounded and converge to the true value in finite time. Fig.5 displays the comparison between the command control torque and actual control torque. The adaptive controller can adjust the actual control output according to the estimated fault to achieve better control performance.

5 Conclusion

In this paper, an adaptive fault tolerant controller for satellite attitude under actuator faults and external disturbances is presented. The loss of effectiveness and bias fault are considered in the actuators. The adaptive controller is designed by employing backstepping and sliding mode technique. According to the Lyapunov theory, the proposed controller ensures that the closed-loop system is globally ultimately uniformly bounded. Numerical simulation results demonstrate that the proposed

IOP Conf. Series: Materials Science and Engineering **608** (2019) 012040 doi:10.1088/1757-899X/608/1/012040

controller can guarantee the attitude control system to converge with fine performance and the faults are effectively estimated by the adaptive law.

References

[1] Tayebi A, Unit Quaternion-Based Output Feedback for the Attitude Tracking Problem, IEEE Transactions on Automatic Control, **53**, 6, 1516-1520 (2008)

[2] Safa A, Baradarannia M, Kharrati H, et al., Robust attitude tracking control for a rigid spacecraft under input delays and actuator errors, International Journal of Control, 1-29 (2017)

[3] Jian Z, Hu Q, Xie W, Integral sliding mode-based attitude coordinated tracking for spacecraft formation with communication delays, International Journal of Systems Science, **48**, 15, 1-13 (2017)

[4] Luo W, Chu Y, Ling K, Inverse optimal adaptive control for attitude tracking of spacecraft, IEEE Transactions on Automatic Control, **50**, 11, 1639-1654 (2005)

[5] Xia Y, Zhang J, Lu K, et al., Adaptive Attitude Tracking Control for Rigid Spacecraft with Finite-Time Convergence, Automatica, **49**, 12, 3591-3599 (2013)

[6] Liang J, Dong C, Wang Q, A fault-tolerant attitude control system for a satellite based on fuzzy global sliding mode control algorithm, Proceedings of SPIE - The International Society for Optical Engineering, **7128**, 3, 35-39 (2008)

[7] Godard G, Kumar K, Fault Tolerant Reconfigurable Satellite Formations Using Adaptive Variable Structure Techniques, Journal of Guidance, Control, and Dynamics, **33**, 3, 969-984 (2010)

[8] Tudoroiu N, Khorasani K, Fault detection and diagnosis for satellite's attitude control system (ACS) using an interactive multiple model (IMM) approach, IEEE Conference on Control Applications, (2005)

[9] Calise A, Hovakimyan N, Idan M, Adaptive output feedback control of nonlinear systems using neural networks, Pergamon Press, (2001)

[10] Ran D, Sheng T, Wang Y, et al., Adaptive Non-singular Terminal Fault-tolerant Control for Rigid Spacecraft Attitude Maneuver, (2017)

[11] Hu Q, Xiao B, Zhang Y, Fault-Tolerant Attitude Control for Spacecraft Under Loss of Actuator Effectiveness, Control & Decision, **34**, 3, 263-268, (2015)

[12] Li Y, Ma Z, Tong S, Adaptive Fuzzy Fault-Tolerant Control of Non-Triangular Structure Nonlinear Systems with Error-Constraint, IEEE Transactions on Fuzzy Systems, **99** 1-1 (2017)

[13] Alwi H, Edwards C, Fault tolerant control using sliding modes with on-line control allocation, Automatica, **44**, 7, 1859-1866, (2008)

[14] Liao F, Lum K, Wang J, et al., Adaptive control allocation for non-linear systems with internal dynamics, IET CONTROL THEORY AND APPLICATIONS, **4**, 6, 909-922, (2010)

[15] Cai G, Hu C, Duan G, Eigenstructure assignment for linear parameter-varying systems with applications, Mathematical & Computer Modelling, **53**, 5-6, 861-870, (2011)

[16] Rodil S, Fuente M, Fault tolerance in the framework of support vector machines based model predictive control, Engineering Applications of Artificial Intelligence, **23**, 7, 1127-1139, (2010)

[17] Deshpande A, Patwardhan S, Narasimhan S, Intelligent state estimation for fault tolerant nonlinear predictive control, Journal of Process Control, **19**, 2, 187-204, (2009)