INTELLIGENT FAULT DETECTION, IDENTIFICATION AND CONTROL OF SATELLITE FORMATION FLYING

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Abstract: A class of nonlinear leader-follower satellite formation flying system subject to uncertain thruster faults and external J_2 disturbances has been studied in this paper with the help of FDI and second order sliding mode control. The faults considered are modeled as constant and time-varying faults which can occur randomly. It is proved that the proposed control scheme can guarantee all signals of the closed-loop system to be semi-globally, uniformly, and ultimately bounded, and the tracking error can converge to a small neighborhood near zero. Simulation results confirm that the suggested control methodologies yield high formation keeping precision and effectiveness for leader-follower formation flying systems. The numerical results demonstrate the effectiveness of the proposed active fault tolerant control under thruster faults.

1 INTRODUCTION

Satellite formation flying (SFF) has been identified as a significant technology for many different space missions. Environmental forces such as gravitational perturbation, atmospheric drag, solar radiation pressure and electromagnetic forces will cause the formation to deviate from the desired trajectory. A low thrust control system for autonomous coordinated multiple satellite formation flying has been studied in great detail. Events such as malfunctions in thrusters, sensors, or other system components can cause severe performance deterioration and system instability leading to catastrophic accidents. The benefits of formation flying can only become available with a robust and reliable fault tolerant control system which is capable of handling potential failures in these systems in order to provide desirable performance (Valdes and Khorasani, 2010) (Edwards et al., 2007) (Wu and Saif, 2007) (Azizi and Khorasani, 2008). According to a recent survey paper (Benosman, 2010), many interesting results have been obtained so far. But work that treats both problems together of nonlinear fault detection and diagnosis and nonlinear fault tolerant control in an effective applicable method, is still missing. Real-life applications of those nonlinear fault tolerant control theories are also a missing part of the recent work. The primary focus of this paper is on developing an intelligent fault tolerant control system for satellite formation flying. The intelligent controller has the ability to adapt the control to the mostly nonlinear process behavior and performs a fault diagnosis to request maintenance and a decision. Active fault tolerant control based on a fuzzy logic system and second order sliding mode observer is developed from the Lyapunov theorem. Compared to other control methods, the proposed control method uses less fuel.

2 SYSTEM MODEL

The satellites are modeled as point masses and therefore the rotational dynamics of the leader and follower satellite are not taken into account. The orbital equations of motion for the leader satellite and the full nonlinear translational dynamics of the follower satellite relative to the leader satellite (shown in Figure 1), taking into account the thrust and disturbance forces, can be written in the following form (Wong et al., 2002): Rewrite the MIMO formation flying system as

$$\dot{X}(t) = \begin{bmatrix} X_2(t) \\ f(t,X,u) \end{bmatrix} + D(t,X,u) \qquad (1)$$

$$X(t) = \begin{bmatrix} X_1(t) \\ X_2(t) \end{bmatrix} \in R^6,\ X_1(t) \in R^3,\ X_2(t) \in R^3.$$

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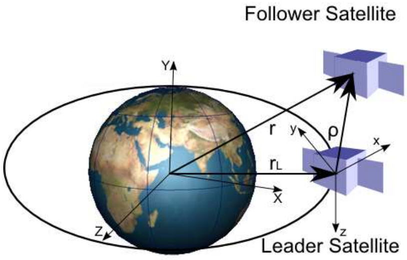

Figure 1: Geometry of orbit motion of leader and follower satellites.

The system model given in Equation 1 with thruster fault is represented as

$$\dot{X}(t) = \begin{bmatrix} X_2(t) \\ f(t,X,u) \end{bmatrix} + \begin{bmatrix} O_{n\times n} \\ g(t,X,u) \end{bmatrix} + D(t,X,u) \quad (2)$$

where $g(t,X,u)$ represents the unknown thruster fault and is bounded.

The normal controller objective (u_n) for formation keeping of the follower satellite relative to the leader satellite requires that the actual position of the follower track the desired relative position trajectory. Third, all signals in the closed-loop system are uniformly, and ultimately bounded. The tracking errors converge to a small neighborhood near zero.

3 FAULT DETECTION AND ACCOMMODATION SCHEME

We now summarize a methodology for designing a fault detection and accommodation scheme, which consists of a second order sliding mode observer and fuzzy identifier. The proposed fault accommodation scheme is designed such that it is capable of detecting and identifying unknown faults.

3.1 Fault Detection and Isolation Scheme

The intelligent and learning based techniques (Neural network, fuzzy logic, and expert system) are more suitable and promising when accurate mathematical models are not available. These methods monitor and approximate any fault behavior in the dynamic system by using on-line approximation and adaptive nonlinear estimation techniques. Fault detection and isolation schemes (FDI) have been researched extensively although few efforts have been made in the area of autonomous fault tolerant control systems for formation flying of satellites.

A second order sliding mode observer with fuzzy identifier scheme is proposed in this paper, based on the second order sliding mode observer with wavelet networks scheme proposed in (Wu and Saif, 2007).

3.1.1 Fault Detection by Second Order Sliding Mode Observer

The second order sliding mode observer is used to observe the system states with modeling uncertainties and disturbance prior to the occurrence of any fault. Based on Equation 1, a nonlinear observer is proposed as

$$\dot{\hat{X}}_1 = \hat{X}_2 + \lambda_1 \quad (3)$$

$$\dot{\hat{X}}_2 = f(t,X_1,\hat{X}_2,u) + \lambda_2 \quad (4)$$

where $\hat{X}_1$ and $\hat{X}_2$ are the state estimations, λ_1 andλ_2 are the correction variables.

The correction variables λ_1 and λ_2 are of the form

$$\lambda_1 = \rho\left|\tilde{X}_1\right|^{0.5} tanh(\tilde{X}_1) \quad (5)$$

$$\lambda_2 = \sigma_1 tanh(\tilde{X}_1) \quad (6)$$

Taking the estimation errors as $\tilde{X}_1 = X_1 - \hat{X}_1$ and $\tilde{X}_2 = X_2 - \hat{X}_2$ (residual), the error equations are written as

$$\dot{\tilde{X}}_1 = \tilde{X}_2 - \rho\left|\tilde{X}_1\right|^{0.5} tanh(\tilde{X}_1) \quad (7)$$

$$\dot{\tilde{X}}_2 = G(t,X_1,X_2,\hat{X}_2,u) - \sigma_1 tanh(\tilde{X}_1) \quad (8)$$

where $G(t,X_1,X_2,\hat{X}_2,u) = g(t,X_1,X_2,U(t,X_1,X_2)) - g(t,X_1,\hat{X}_2,U(t,X_1,X_2)) + D(t,X_1,X_2,U(t,X_1,X_2))$. According to the reference (Davila et al., 2005), G is assumed to be bounded and ρ, σ_1 can be chosen by

$$\begin{aligned} \left|G(t,X_1,X_2,\hat{X}_2,u)\right| &< g^* \\ \rho &> \sqrt{\frac{2}{\sigma_1 - g^*}}\frac{(\sigma_1+g^*)(1+\eta)}{1-\eta} \\ \sigma_1 &> g^* \end{aligned} \quad (9)$$

where η is a constant $(0 < \eta < 1)$.

We can find $\left\|\tilde{X}_1\right\| \leq \tilde{X}_M$ (threshold bound chosen by experiments). The decision for detecting a fault is made when $\left\|\tilde{X}_1\right\|$ exceeds its threshold bound $\tilde{X}_M$.

3.1.2 Fault Isolation by Fuzzy Identifier

For a real nonlinear system, it is quite difficult to determine a priori what class of faults may occur. As the fault is unknown, it is also difficult to isolate the fault function. Therefore, we only present constant fault functions in this paper. In future work, we will give all possible fault functions (constant, time-varying, and ramp fault) for finding a fault type. The isolation observers corresponding to one of the possible types of faults are proposed as

$$\dot{\hat{X_{r1}}} = \hat{X_{r2}} + \lambda_1 \quad (10)$$
$$\dot{\hat{X_{r2}}} = f(t, X_{r1}, \hat{X}_{r2}, u) + \lambda_2 + \gamma(t - Tf)\hat{g} \quad (11)$$

where $\hat{X_{r1}}$ and $\hat{X_{r2}}$ are the state estimations for one of the possible types of faults, λ_1 andλ_2 are the correction variables, and $\hat{g}$ is a fuzzy identifier to specify the process fault. The term Tf is the time to activate the fuzzy identifier.

In this paper, a fuzzy identifier (Wang, 1997) is used to determine the fault location and to estimate its magnitude. The fuzzy logic system is a collection of IF-THEN fuzzy rules such as:

$$R^k \ : \ IF \ x_1 \ is \ A_1^k, \ and, \ \cdots, \ x_n \ is \ A_n^k, \quad (12)$$
$$THEN \ y \ is \ B^k.$$

The output of the fuzzy system (using singleton fuzzification, product inference and center average defuzzification) can be written as :

$$y_{out} = \frac{\sum_{l=1}^{P} \theta_F^l(X) \prod_{i=1}^{N} \mu^l_{Ai^l(x_i)}}{\sum_{l=1}^{P} \prod_{i=1}^{N} \mu^l_{Ai^l(x_i)}} = \theta^T \xi \quad (13)$$

where P is the total fuzzy rules number, the membership functions $\mu_{A1^l(x_1)}, \ldots, \mu_{An^N(x_n)}$ (N is the number of membership functions) are Gaussian functions, and ξ is the fuzzy basis function $\left(\xi^l(x) = \frac{\prod_{i=1}^{N} \mu_{Ai^l(x_i)}}{\sum_{l=1}^{P} \prod_{i=1}^{N} \mu_{Ai^l(x_i)}}\right)$. We use the fuzzy system $\hat{g}(t, X, u \mid \theta_g) = \theta_g^T \xi_g(t, X, u)$ to approximate $g(t, X, u)$.

It is assumed that there exists an optimal fuzzy logic system to learn the nonlinear terms $g(t, X, u)$ such that

$$g(t, X, u) - g^*(t, X, u \mid \theta_g^*) = w_G(t, X, u) \quad (14)$$

where w_G is approximation error and is bounded. Approximation error can be reduced by increasing the number of fuzzy rules. However, in order to decrease the size of the fuzzy rules, we use the sliding surface $\sigma(t)$ instead of X as the input of the fuzzy logic system. Simulation shows that this produces reasonable results compared to using X.

3.2 Fault Accommodation Scheme

3.2.1 Normal Controller

The general chattering-free sliding mode control law with the saturation function is given by

$$v(t) = -k sat(\sigma/\varepsilon), \quad (15)$$

where ε is a small positive constant.

The 2nd SMC fault tolerant control design of the authors in reference (Li et al., 2010) is proposed as:

$$v(t) = -k_1\sigma(t) - k_2 \int_0^t \sigma(t)dt \quad (16)$$

With this chattering-free 2nd SMC law, the system enters a vicinity of the 2nd-SM $\sigma(t) = \dot{\sigma}(t) = 0$ and then to a vicinity of the origin, locally and asymptotically.

We then apply the 2nd order sliding mode control for satellite formation flying. Rewrite the nonlinear dynamics model of formation flying (equation 1) as $f(t, X, u) = AX + E(X)$. The new 2nd sliding mode controller is written as

$$u_n(t) = -k_1\sigma(t) - k_2 \int_0^t \sigma(t)dt - C_g[AX + E(X) - \ddot{X}d] \quad (17)$$

where $C_g = \begin{bmatrix} 2 & 0 & 0 & 1 & 0 & 0 \\ 0 & 2 & 0 & 0 & 1 & 0 \\ 0 & 0 & 2 & 0 & 0 & 1 \end{bmatrix}$.

3.2.2 Accommodation Control of System failures

After fault isolation, the fault tolerant 2nd SMC law with fuzzy identifier is designed as

$$u = u_n + u_f \quad (18)$$

Rewrite the term $\hat{g}(t, X, u \mid \theta_g)$ in equation 14 as $\hat{g}_r(t, \sigma, u \mid \theta_g)$. $\hat{g}_r(t, \sigma, u \mid \theta_g) = \theta_g^T \xi_g(t, \sigma, u)$, where $\dot{\theta}_g = \alpha\sigma\xi_g$. The controller to accommodate the fault is $u_f = \theta_g^T \xi_g(t, \sigma, u)$.

4 RESULTS AND DISCUSSION

The desired formation considered for ideal formation keeping is a projected circular formation. The phase angle (ϕ) between the leader and follower satellite is assumed to be zero. The initial states for the numerical simulation are computed by substituting $t = 0$ and adding a 1 km position offset on x, y, and z. All simulation cases are assumed to run 4 orbits. The SFF system parameters and the orbital parameters for the leader satellite used in the numerical simulations are given in Table 1.

4.1 Constant Fault Case

We use the thruster constant additive fault scenario in this study as: $T_{ti} = \begin{cases} 0 & t < t_f \\ 5 \times 10^{-1} N & t \geq t_f \end{cases}$

Periodic additive fault is assumed to be permanently added to all thrusters after 0.5 orbits. The

Table 1: Satellite Parameters.

Parameter	Value
m_F (kg)	1
μ_e (km^{3}s^{-2})	398600
r_L (km)	6878
e	0.1
i (deg)	45
ϕ (deg)	0
Ω, ω, i, M (deg)	0

3D trajectory with fault detection, isolation and accommodation is shown in Figure 2(a). The formation keeping is still available after the fault using the fault tolerant 2nd SMC law. Figure 2(b) shows relative position errors and control demand for formation keeping. The steady-state errors on the radial, along track, and cross track directions are bounded by 3 m. Then, we use the proposed second sliding mode observer with fuzzy identifier for fault detection and isolation. The threshold $\tilde{X_M}$ is assumed as $100m/s^2$. The faults T_{ti} (i=1,2,3) and fault isolation results $\hat{T}_{ti}$ (i=1,2,3) are given in Figures 2(c), 2(d) and 2(e). The fault added on the actuator of the radial, along track, and cross track directions are isolated using the fuzzy logic identifier.

4.2 Time-varying Fault Case

In order to test the robustness for other faults, we use the time-varying additive fault scenario in this study as:

$$T_{ti} = \begin{cases} 0 & t < t_f \\ 5 \times 10^{-2} \times cos(2 \times 10^{-4} 3.14159t)N & t \geq t_f \end{cases}$$

Figure 3(a) shows relative position errors and control demand for formation keeping. The steady-state errors on the radial, along track, and cross track directions are bounded by 80 m. The faults T_{ti} (i=1,2,3) and fault isolation results $\hat{T}_{ti}$ are given in Figures 3(b), 3(c) and 3(d). The residuals are shown in Figure 3(e). The fault detection and isolation results are as good as that of the constant fault case. The fault accommodation control results for time-varying faults are reasonable.

5 CONCLUSIONS

This paper presents an analysis of satellite formation keeping using a fault diagnosis and control scheme based on a second order sliding mode observer, fuzzy identifier and second order sliding mode controller. The thruster faults considered are modeled as constant and time varying additive faults which occur at unknown times. Results of numerical simulation indicate that the proposed FDI and fault tolerant control methodology can force the formation keeping error to converge to a small neighborhood near zero (less than 3m under constant case and less than 80m under time varying fault). Moreover, the numerical results clearly establish the robustness of the proposed fault detection, identification and control methodologies in tracking a desired formation even in the presence of thruster faults as well as time-varying disturbances.

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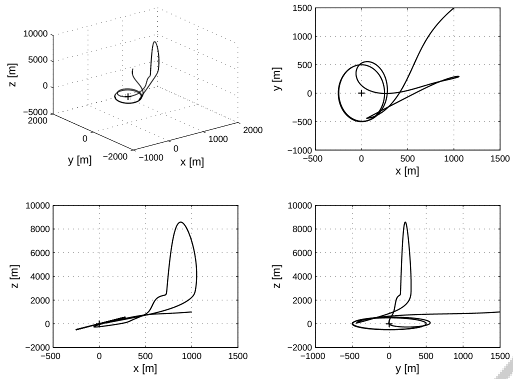
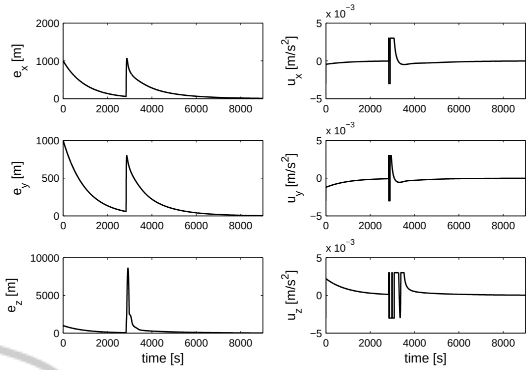
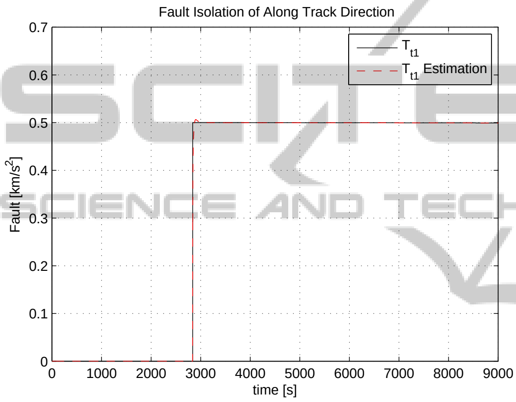


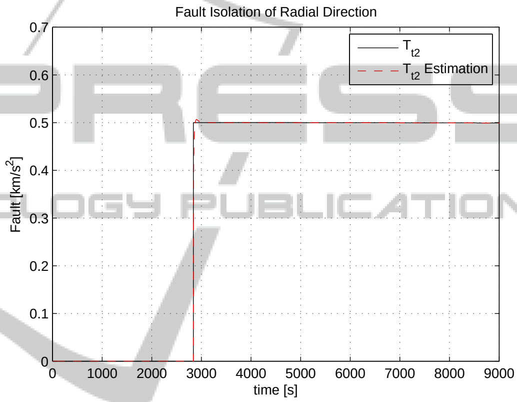
(a) 3D Trajectory with FTC



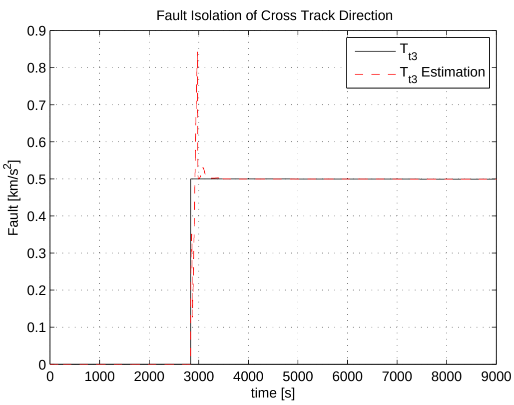
(b) Relative Position Errors and Control Input



(c) Constant Thruster Fault Isolation

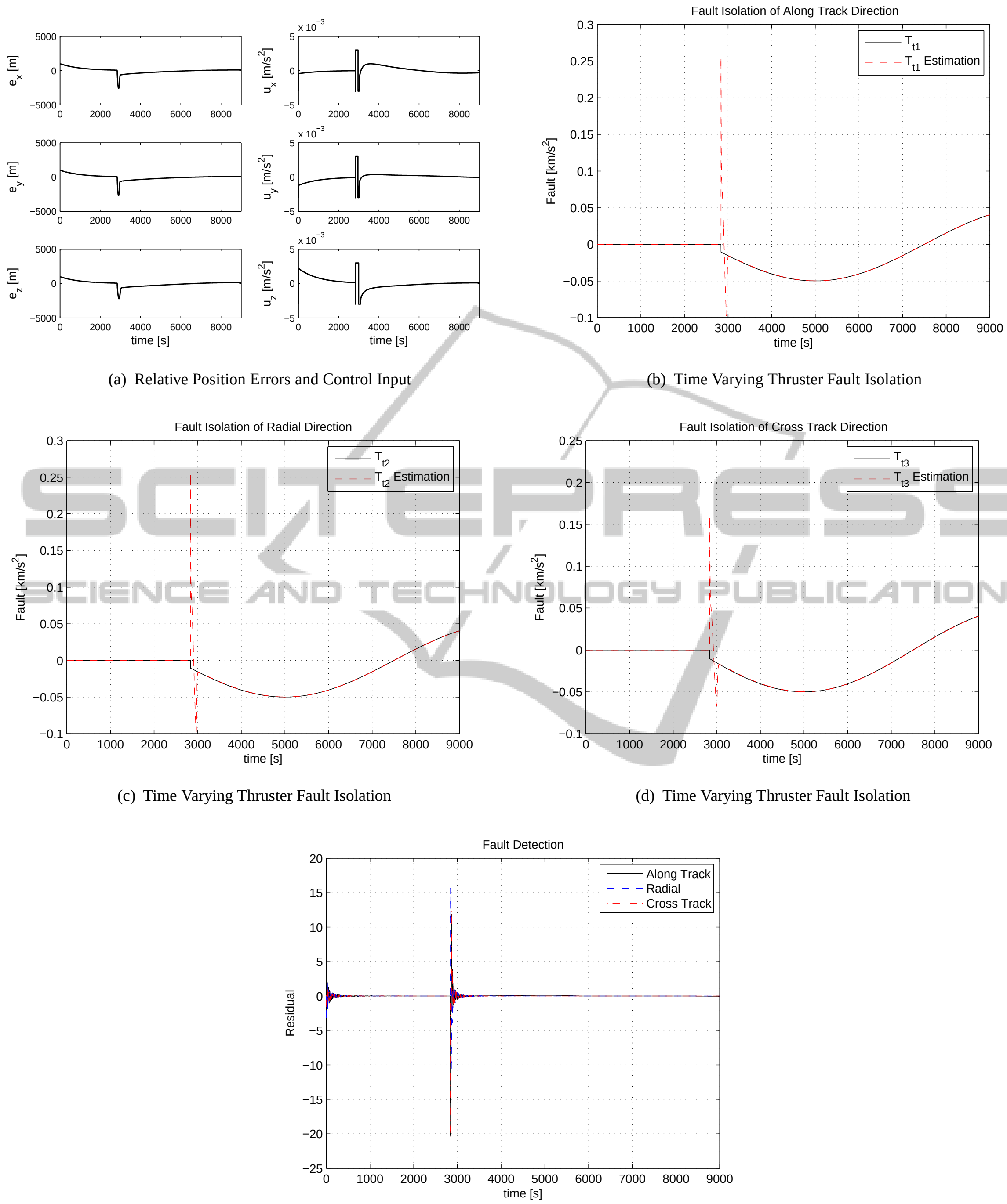


(d) Constant Thruster Fault Isolation



(e) Constant Thruster Fault Isolation

Figure 2: Fault Tolerant Control and Fault Isolation Simulation under Constant Thruster Fault.



(a) Relative Position Errors and Control Input

(b) Time Varying Thruster Fault Isolation

(c) Time Varying Thruster Fault Isolation

(d) Time Varying Thruster Fault Isolation

(e) Residual of Fault Detection by 2nd SM Observer

Figure 3: Fault Tolerant Control and Fault Isolation Simulation under Time Varying Thruster Fault.