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Satellite Flatness based Fault Tolerant Control

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ABSTRACT

Applying flat systems technique in attitude fault tolerant control of an under-actuated satellite has been investigated in this article. The main purpose of this study is development and implementation of a new idea in order to recovery of satellite stability and its acceptable performance in actuator fault scenarios. Solving the attitude fault tolerant control problem is based on consideration a realistic assumption which can show the ability of FTC system in managing the fault scenarios. Lose of effectiveness of actuators which could be caused in many of fault scenarios, modeled and simulated by multiplicative model. Thanks to provided new idea in this study it will be proven that, a wide range of actuator fault scenarios with different intense of faults could be managed without need to reconfiguring the main controller. Usage of this idea affects in reducing the volume of main controller computations and provides an appropriate base for its robust designing in other to dealing with systematically fault scenarios. Furthermore, the provided active fault tolerant attitude control scheme uses analytical redundancy system which could be considered as analytical observer. The suggested analytical observer by this technique, which belongs to nonlinear observer category, can observe all of the dynamic variables in allowable range of error. Practical implications of this study belong in this fact which analytical redundancy based on new idea in order to maintaining stability could be a perfect option in different fault scenarios such as systematically uncertainties and sensor faults. Hence this idea could be implemented without need to any physical instrument.

General Terms

Fault tolerant, flatness based control.

Keywords

Flat differential technique; flatness based attitude control; nonlinear systems

1. INTRODUCTION

The performance of controlled system directly depends on correct operation of each close loop sub systems. Even small physical or functional faults on each sub systems such as actuators and sensors could effect on stability as the most important performance characteristic of controlled system. Among the wide range of probable faults on controlled system, actuator faults could create dangerous and harsh fault scenarios. Fault tolerant control (FTC) systems are supposed to ensure stability and best possible performance of the control loop even in the case of faults in actuators, sensors or other components of the system [1]. This ability can be made by different strategies. Some of these strategies based on robust property of controller which belong to passive FTC category [2]. Other strategies based on fault detecting and reconfiguring the controller and belong to active FTC category [3]. In active FTC, FDI plays a vital role in providing information about faults/failures in the system to enable appropriate reconfiguration to take place. The main function of FDI is to detect a fault or failure and to find its location so that corrective action can be made to eliminate or minimize the effect on the overall system performance [4]. The most researched area in FDI is the residual generation approach. Examples of recent residual based FDI research methods appear in Marcos et al [5], Szaszi et al [6] based on $H\infty$ ideas.

Although active FTC schemes have excellent ability to managing wide range of different fault scenarios, but reconfiguration of controller require to passing a boring design procedure. Hence achieving to perfect active FTC scheme without requiring to reconfigurable controller has been considered as one of the main goals in this research field. In this study by providing a new idea in active FTC scheme based on flatness property of system equations, it will be shown that a wide range of actuator fault scenarios could be managed.

2. FLAT DIFFERENTIAL FRAMEWORK

Flat differential is an operational technique of physical systems which is based on a unique property in dynamic equations structure [7] Based on this property, all of the state variables of system could be observed analytically by means of re-expression of governing equations in square differential flatness framework. Thereupon a sort of full nonlinear state observer could be presented by this property. Hence the main disadvantage of almost nonlinear methods could be removed. Also, this property could be considered as a perfect option in fault tolerant control problem, in other to reducing the number of dealing variables. One of the most popular nonlinear control methods which has been investigated based on the flat technique is the Feedback linearization. In feedback linearization method, the control command is applied to the system in such a way that system error dynamic comes in the form of a linear differential set. This method has been used on guidance and control of reentry vehicles [8] and satellites attitude control [9] in aerospace engineering.

In a flat system there is a set of independent differential outputs variables which can parameterize all of the dynamic variables and control inputs as function of these flat outputs and their highest derivatives. The number of flat variables exactly equal to number of system control inputs. Hence by created square differential framework, any set of differential equation could be reduced. This property is important especially in those systems which suffer from dealing with different variables. The introduction of the method and some case studies has been mentioned in [10].

If a set of nonlinear differential equations are considered in general form:

$$\dot{x} = f(x,u) \tag{1}$$

Where $x \in R^n$ expresses the state variables of system and $u \in R^m$ expresses the control input of system, which $m \le n$. System 1 is called Flat System if an independent vector of outputs or their combinations in form of $F \in R^m$ have been found in such a way that all of the system variables and also all of the control inputs could be expressed as functions of these flat variables and finite number of their derivatives. In other word the above statement could be considered as the two conditions of flattened differential system which could be expressed in mathematical form as follow:

$$\begin{aligned} x &= \varphi(F, \dot{F}, \ddot{F}, \ldots, F^{(s)}) \\ u &= \psi(F, \dot{F}, \ddot{F}, \ldots, F^{(s)}, F^{(s+1)}) \end{aligned} \tag{2}$$

Where, S is an integer elemental vector which expresses the order of derivatives of variables $S = (S_1, S_2, \ldots, S_m)$. And also F is a function of x , u and finite number of the u such as below:

$$F = \zeta(x, u, \dot{u}, \ddot{u}, \ldots, u^{(r)}) \tag{3}$$

Where, r is a positive integer.

3. SATELLITE FLATNESS BASED ATTITUDE CONTROL

In this section, attitude dynamic equation of a sample under-actuated satellite has been investigated as case study. The system, which has been borrowed from [11], is given by following equations:

$$\begin{cases} J_1 \dot{\omega}_1 = \alpha \omega_2 \omega_3 + u_1 \\ J_2 \dot{\omega}_2 = \beta \omega_1 \omega_3 + u_2 \quad , \; y_i = \omega_i \quad i \in \{1,2,3\} \\ J_3 \dot{\omega}_3 = \gamma \omega_1 \omega_3 \end{cases} \tag{4}$$

Where, the state component ω_i, $i \in \{1,2,3\}$ denotes the angular velocity around the ith principal axis of rotation, u1, u2 denotes the input signals (thrust modules), y_i, $i \in \{1,2,3\}$ denote the measured angular velocities. The constants J_i, $i \in \{1,2,3\}$ signify the moments of inertia around the ith axis of rotation and for selected sample satellite are equal to $J_1 = 0.4, J_2 = 0.5, \; J_3 = 0.55 \; Kg.m^2$. Finally α, β, γ are given by:

$$\begin{cases} \alpha = J_2 - J_3 \\ \beta = J_3 - J_1 \\ \gamma = J_1 - J_2 \end{cases} \tag{5}$$

The flatness property of the satellite model is demonstrated. Usage of Flatness technique in control algorithm of special case study depends on success in flat proofing of dynamic behavior of that system. Accordingly based on flat system definition, a set of system output variables have been considered as below:

$$\begin{cases} F_1 = \omega_1 \\ F_2 = \omega_3 \end{cases} \tag{6}$$

Based on selected flat variables all of dynamic variable and control inputs can be parameterized as functions of these variables and their finite derivatives.

$$\begin{cases} \omega_1 = F_1 \\ \omega_2 = \dfrac{J_3}{\gamma}\left(\dfrac{\dot{\omega}_3}{\omega_1}\right) \\ \omega_3 = F_2 \end{cases} \Rightarrow \begin{cases} \omega_1 = \varphi_1(F_1) \\ \omega_2 = \varphi_2(F_1, \dot{F}_2) \\ \omega_3 = \varphi_3(F_2) \end{cases} \tag{7}$$

And,

$$\begin{cases} u_1 = J_1 \dot{\omega}_1 - \dfrac{J_3 \alpha}{\gamma}\left(\dfrac{\dot{\omega}_3 \, \omega_3}{\omega_1}\right) \\ u_2 = \dfrac{J_2 J_3}{\gamma}\left(\dfrac{\ddot{\omega}_3 \, \omega_1 - \dot{\omega}_3 \, \dot{\omega}_1}{\omega_1^{\,2}}\right) - \beta \omega_1 \omega_3 \end{cases} \Rightarrow \begin{cases} u_1 = \psi_1(F_1, \dot{F}_1, F_2, \dot{F}_2) \\ u_2 = \psi_2(F_1, \dot{F}_1, F_2, \dot{F}_2, \ddot{F}_2) \end{cases} \tag{8}$$

According to the information gained in the procedure of demonstrating of flat variables, there was a similarity between the control command generating in feedback linearization and flat functions of control inputs and dynamic variables. This similarity leaded to using the flat systems technique for mentioned control method. Feedback control law could be generated by substituting the highest derivative terms with the following suggested form in the obtained control functions, ψ_i.

$$\begin{cases} \dot{F}_1 = \upsilon_1 \\ \ddot{F}_2 = \upsilon_2 \end{cases} \Rightarrow \begin{cases} \upsilon_1 = \dot{F}_{1ref} + K_{1P}(F_{1ref} - F_1) \\ \upsilon_2 = \ddot{F}_{2ref} + K_{2D}(\dot{F}_{2ref} - \dot{F}_2) + K_{2P}(F_{2ref} - F_2) \end{cases} \tag{9}$$

Where, υ_i, $i \in \{1,2\}$ are the feedback control laws and $F_{i\,ref}$, $i \in \{1,2\}$ are reference trajectories of flat variables. The proposed Flatness Based attitude control is illustrated in figure (1).

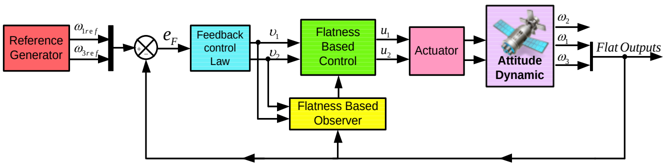

Fig 1: Implication of Flatness Based Attitude Control

4. FLATNESS BASED FAULT TOLERANT CONTROL

In order to achieving an active FTC, the concept of analytical redundancy has been considered. The basic assumption of solving the fault tolerant control problem is based on the fact that, there is not available redundant actuator in fault scenarios. With this realistic assumption, entire duty of managing fault scenarios must be carried by attitude control. Hence the ability of used control method in FTC scheme can be investigated. This paper presents an innovative approach to maintaining satellite stability in FTC field. In this approach the flatness property of system dynamics has been used. Lose of effectiveness of actuators which could be caused in many of fault scenarios, modeled and simulated by multiplicative fault model [12].

The main focus of this article is providing a new idea which can guarantees the possible performance and stability of satellite in actuator fault scenarios. An active fault tolerant control system identifies any actuator faults by use of fault detection and identification (FDI) block. Accordingly an axillary control command, uf could be generated based on residual signals and add to main control command, u_{nom}, as shown in figure 2.

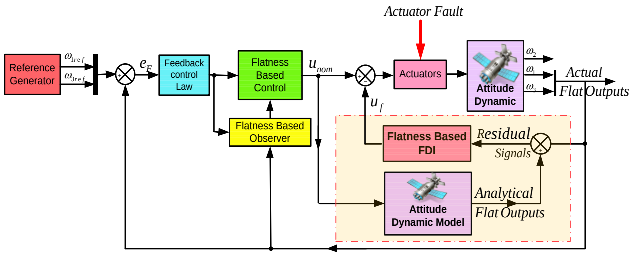

Fig 2: common Active FTC Scheme

This is a general strategy of active FTC in actuator fault scenarios. Management of these conditions carries out by the main controller and FDI block corporately. Hence success in management of fault scenarios depends on a reliable reconfiguration which is necessary for the main controller.

The new provided idea in this article based on this fact that, management of actuator fault scenarios does not depend on accessing a reconfigurable controller and could be done only by residual based FDI system. As shown in figure 3 this idea could be implementable only by feed backing free fault flat outputs obtained from analytical redundancy system into the main controller. By this strategy, the main controller generates free fault control command and entire duty of fault scenario carry out only by residual based FDI block.

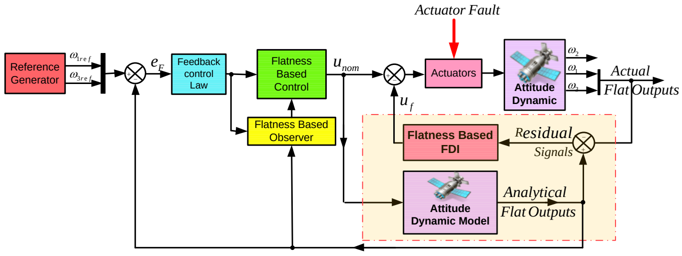

Fig 3: Active FTC scheme based on New Idea

From an FTC point of view, the benefits of this scheme are that the controller structure does not have to be reconfigured in the case of actuator faults. Feedback control law of residual based FDI block compensates faulty flat variables. The reference trajectories of flat variables for FDI compensation are analytical flat outputs which are obtained from analytical redundancy.

$$\begin{cases} \dot{F}_1 = \upsilon_{1f} \\ \ddot{F}_2 = \upsilon_{2f} \end{cases} \Rightarrow \begin{cases} \upsilon_{1f} = \dot{F}_{1anl} + K_{1P}(F_{1anl} - F_1) \\ \upsilon_{2f} = \ddot{F}_{2anl} + K_{2D}(\dot{F}_{2anl} - \dot{F}_2) + K_{2P}(F_{2anl} - F_2) \end{cases} \tag{10}$$

$$\begin{cases} u_{1f} = J_1\upsilon_{1f} - \dfrac{J_3\alpha}{\gamma}\left(\dfrac{\dot{F}_2 F_2}{F_1}\right) \\ u_{2f} = \dfrac{J_2 J_3}{\gamma}\left(\dfrac{\upsilon_2 F_1 - \dot{F}_2\upsilon_{1f}}{F_1^2}\right) - \beta F_1 F_2 \end{cases} \tag{11}$$

Where, $\upsilon_{if},\ i \in \{1,2\}$ are faulty feedback control laws and $u_{if},\ i \in \{1,2\}$ are identified actuator faults.

5. Simulation and Results

In order to showing the performance of presented satellite flatness based FTC, two actuator fault scenario has been simulated in MATLAB/Simulink. Each of these scenarios have the same reference trajectories of flat variables, but different in fault scenario. Reference trajectories of flat variables have been designed to change the satellite attitude from initial rest condition to another rest condition. The initial and final conditions for flat variables are as below:

$$\text{Initial Conditions} \begin{cases} F_{1initial} = 1\ rad\ ,\ \dot{F}_{1initial} = 0\ \ rad/s \\ F_{2initial} = 2\ rad\ ,\ \dot{F}_{2initial} = 0\ \ rad/s \end{cases}$$

$$\text{Final Conditions} \begin{cases} F_{1final} = 2\ rad\ ,\ \dot{F}_{1final} = 0\ \ rad/s \\ F_{2final} = 4\ rad\ ,\ \dot{F}_{2final} = 0\ \ rad/s \end{cases} \tag{12}$$

For satisfying above conditions third order polynomial functions has been considered as below:

$$\begin{cases} F_{1ref} = 0.0015t^3 + 0.0248t^2 + 1 rad/s \\ F_{2ref} = -0.003t^3 + 0.049t^2 + 2 = 0\ \ rad/s \end{cases} \tag{13}$$

Loss of effectiveness of each actuator has been investigated separately as fault scenarios. The results have been shown in Fig 4 -9.

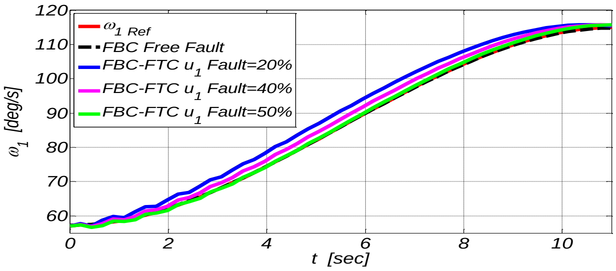

Fig 4: Tracking Reference Flat Variable ω_1, in Fault Scenario of First Actuator u_1

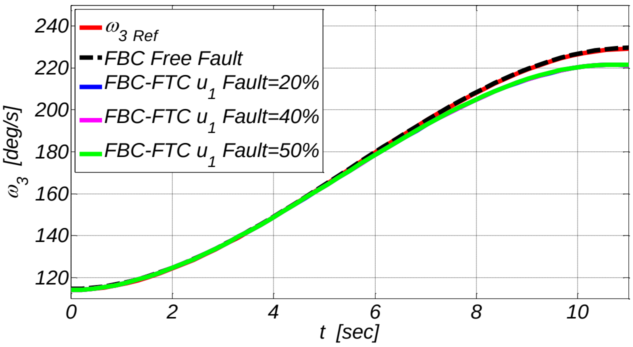

Fig 5: Tracking Reference Flat Variable ω_3, in Fault Scenario of First Actuator u_1

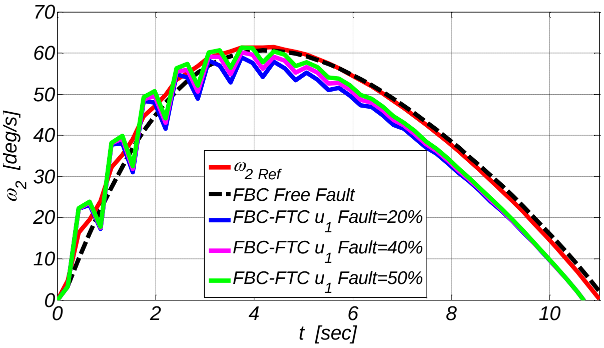

Fig 6: Observing Variable ω_2, in Fault Scenario of First Actuator u_1

As shown in figure 4 and figure 5, the satellite attitude FTC system based on new provided idea without require to reconfiguration can manage the fault scenario even up to 50 percentage fault in first actuator. Results show that, stability of satellite during attitude maneuvers has been safe maintained. Figure 6 shows the ability of flatness based observer even in fault scenarios.

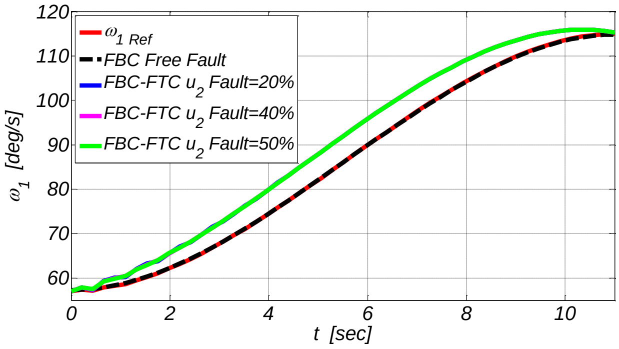

Fig 7: Tracking Reference Flat Variable ω_1, in Fault Scenario of First Actuator u_2

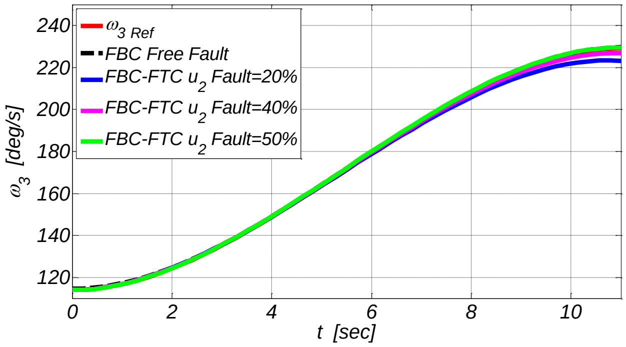

Fig 8: Tracking Reference Flat Variable ω_3, in Fault Scenario of First Actuator u_2

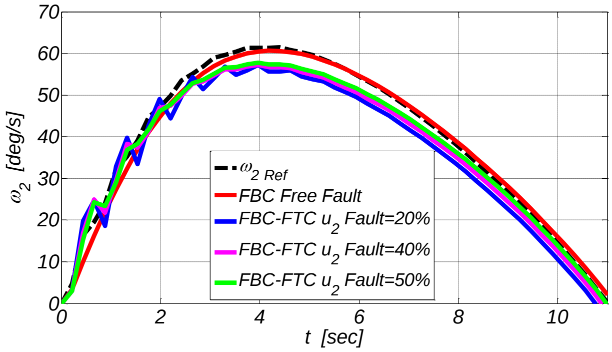

Fig 9: Observing Variable ω_2, in Fault Scenario of First Actuator u_2

Also as shown in figure 7 and figure 8, the satellite attitude FTC system can manage the fault scenario even up to 50 percentage fault in second actuator. Results show that, stability of satellite during attitude maneuvers has been safe maintained. Figure 9 shows the ability of flatness based observer even in fault scenarios. All flat variables have allowable range of error in tracking reference trajectory.

6. CONCLUSION

In this paper a new approach for dealing fault tolerant control problem on satellite attitude dynamic has been investigated. In order to achieving an active scheme of FTC, a new idea based on separating the main controller from fault compensation has been provided. The main attitude controller has been used from flatness differential property which demonstrated for that dynamics. Nonlinear flatness based observer could estimate all dynamic variables even in fault scenarios with allowable range of error. By this idea active FTC scheme did not required to reconfiguration and possible performance whit 50 percentages fault in actuator was accessible. Consequence of this paper could create an appropriate base for complete intelligent active FTC scheme which require to reconfiguration in systematical fault scenarios.

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