Actuator fault reconstruction using FDI system based on sliding mode observers

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Abstract: *Interplanetary space missions require spacecraft autonomy in order to fulfill the mission objective. The fault detection and isolation (FDI) system increases the level of autonomy and can ensure the safety of the spacecraft by detecting and isolating potential faults before they become critical. The proposed FDI system is based on an innovative bank of SMOs (sliding mode observers), designed for different fault scenarios cases. The FDI system design aims to detect and isolate actuators and measurement units' faults used by the satellite control system and considers the nonlinear model of the satellite dynamics. This approach gives the possibility of fault reconstruction based on the information provided by an equivalent injection signal, allowing to reconstruct external perturbances and faults. The SMO chattering phenomenon is avoided by using the pseudo-sliding function, being a linear approximation of the signum function, which gives the possibility of using the equivalent injection signal for fault reconstruction purposes. The proposed fault reconstruction methodology is illustrated by a case study for a 6U Cubesat.*

Key Words: *fault reconstruction, nonlinear spacecraft dynamics, sliding mode observers, fault detection and isolation, chattering, pseudo-sliding, equivalent injection signal, sliding mode observers bank*

1. INTRODUCTION

The presence of an FDI system for interplanetary missions is of great importance in order to reduce mission risks, detect faults and take actions before the fault escalates and propagates into the systems. Moreover, due to the considerable distances between the spacecraft and earth, in order of astronomical units, the communication delay plays an important role and corrective actions cannot be taken in a short time. Such a mission is HERA [6] with the CubeSat Juventas [7], for which an innovative FDI system (design based on SMOs) to detect and isolate faults in the satellite control system is proposed in the following sections. For FDI testing purposes, a dedicated satellite attitude control system is developed taking into consideration the CubeSat architecture defined in [7] and [9]. The satellite nonlinear dynamic modeling and attitude control system is based on [3], further adapted considering the specifics of the 6U CubeSat. The attitude control system design is a complex task that involves mainly the control law design but also additional features designed to increase the representativeness of the simulation. The FDI simulator consists of the following features, [1]:

- PD controller, that ensures the satellite control,

- Actuator model, considering actuator datasheet information,
- Satellite model, based on dynamic and kinematic equations of motion for the 6U CubeSat,
- Reaction wheel momentum dumping – for flywheel momentum dumping,
- Solar radiation pressure (SRP), to model disturbance torque using the Cannonball model,
- FDI based on SMO bank.

The observer is based on the sliding mode control theory (SMC) introduced in [8] and [2]. Due to common mathematical background, the SMO inherits the performances and robustness of SMC, being suitable for nonlinear systems. SMOs for nonlinear dynamic systems have been considered in [5] and [2], where their use in FDI schemes has been proposed. In the beginning, the field of FDI systems based on SMOs has been overlooked due to the robustness of the method to bounded disturbances and dynamic uncertainties. A major contribution to improving the SMOs performances has been brought in [2] by introducing the so-called equivalent injection signal for faults detection and isolation.

Considering the advantage of the SMC theory, the concept was quickly integrated into the aerospace industry in order to try to build reliable fault-tolerant sliding mode schemes ([10] and [4]), but is still not well spread in the space sector. In [4] the author is focusing on the implementation and performance evaluation of FDI with SMOs which targets a real platform called Mars Express Satellite. The chattering effect is the main issue of control problems using SMC theory. The chattering is the effect of high-frequency oscillation along the sliding surface which can damage the actuator irreversible. In [4] different approaches for mitigating the effect of the chattering are evaluated, mainly using smoothed sliding mode surfaces or implementing a higher order sliding mode. In the present paper, the FDI task is ensured by taking advantage of an innovative bank of SMOs using a continuous approximation based on a sigmoid function, called pseudo-sliding. Moreover, disturbances are considered to increase the fidelity of the simulation and evaluate the FDI performances.

The proposed nonlinear design methodology on the FDI system is illustrated by a case study for a 6U CubeSat. More information about the 6U CubeSat architecture, physical characteristics and mission requirements may be found, for instance, in [9].

2. SATELLITE DYNAMICS

In order to design the FDI based on SMOs, the satellite model must be first defined. The CubeSat is considered a rigid body, modeled as a rectangle shape, with six degrees of freedom composed of translation and rotational states. The satellite's angular velocity and attitude can be derived from the dynamic and kinematic equations [3].

Thus, the satellite angular velocities are derived from Euler's rotation equations which are first-order differential equations [3]:

$$\dot{\boldsymbol{\omega}} = \boldsymbol{I}_s^{-1}\left[-\left(\boldsymbol{\omega} \times (\boldsymbol{I}_s\boldsymbol{\omega} + \boldsymbol{I}_{rw}\boldsymbol{\omega}_{rw})\right) + \boldsymbol{T}_c + \boldsymbol{T}_d\right] \tag{1}$$

where $\boldsymbol{\omega}$ is the satellite angular velocity vector represented in the body frame, $\boldsymbol{I}_s$ is the satellite's inertia tensor, $\boldsymbol{I}_{rw}$ is the reaction wheels inertia tensor, $\boldsymbol{\omega}_{rw}$ reaction wheels angular velocity vector, $\boldsymbol{T}_d$ are the external and internal disturbance torques acting on the satellite and $\boldsymbol{T}_c$ is the control torque generated by actuators (reaction wheels and/ or thrusters).

The satellite attitude representation in a quaternion form is represented as first-order differential kinematic equations [3]:

$$\dot{\boldsymbol{q}} = \frac{1}{2}\boldsymbol{q} \otimes \begin{bmatrix} 0 \\ \boldsymbol{\omega} \end{bmatrix} \tag{2}$$

where ⊗ denotes quaternion product, [11].

3. FDI DESIGN BASED ON SMO

The FDI's main purpose is to raise an alarm when a fault is occurring and to isolate it, if possible. This paper presents an FDI scheme, based on a mathematical model taking advantage of the possibility to approximate the satellite motion with the dynamic and kinematic equations. The mathematical model cannot be known with certainty due to parametric uncertainties and unknown disturbances. To cope with these unknowns, the FDI system must be robust enough to overcome the modeling approximation. Moreover, the satellite dynamics is complex, due to the presence of nonlinearities. Usually, FDI systems use robust design methods taking advantage of techniques like artificial intelligence, linear quadratic estimation or state space observers. The FDI presented in this paper is a version of state space observers based on SMO, being a method suitable for nonlinear systems.

The SMO design is based on SMC theory by using a sliding surface that forces the states of the system to fall on a predesigned surface. The SMO mathematical model follows the structure presented in [5], which uses the signum function:

$$\dot{\widehat{\boldsymbol{\omega}}} = \boldsymbol{I}_s^{-1}\left[-\left(\widehat{\boldsymbol{\omega}} \times (\boldsymbol{I}_s\widehat{\boldsymbol{\omega}} + \boldsymbol{I}_{rw}\boldsymbol{\omega}_{rw})\right) + \boldsymbol{T}_c\right] + \rho\boldsymbol{sgn}(\boldsymbol{\omega} - \widehat{\boldsymbol{\omega}}) \tag{3}$$

where, by "^" is denoted the state estimation.

The objective of the SMO is to minimize the error between $\boldsymbol{\omega}$ and $\widehat{\boldsymbol{\omega}}$ to a minimum:

$$\boldsymbol{e} = \boldsymbol{\omega} - \widehat{\boldsymbol{\omega}} \tag{4}$$

The derivative error equation can be derived from (4), as follows:

$$\dot{\boldsymbol{e}} = \dot{\boldsymbol{\omega}} - \dot{\widehat{\boldsymbol{\omega}}} \tag{5}$$

Equation (4) and implicitly equation (5) can be written component-wise:

$$e_i = \omega_i - \widehat{\omega}_i \tag{6}$$

where *i* represents the array component.

To develop the sliding mode conditions the η-reachability condition is tested, in accordance with [2]:

$$\begin{aligned} e_i\dot{e}_i &= e_i\left(\left(f_i - \hat{f}_i\right) - \rho sgn(e_i)\right) \\ &\leq -|e_i|\left(-\left|f_i - \hat{f}_i\right| + \rho\right) \end{aligned} \tag{7}$$

where f_i and $\hat{f}_i$ denote the array components of $\boldsymbol{f} = -\boldsymbol{I}_s^{-1}\left(\boldsymbol{\omega} \times (\boldsymbol{I}_s\boldsymbol{\omega} + \boldsymbol{I}_{rw}\boldsymbol{\omega}_{rw})\right) + \boldsymbol{I}_s^{-1}\boldsymbol{T}_d$ respectively $\hat{\boldsymbol{f}} = -\boldsymbol{I}_s^{-1}\left(\widehat{\boldsymbol{\omega}} \times (\boldsymbol{I}_s\widehat{\boldsymbol{\omega}} + \boldsymbol{I}_{rw}\boldsymbol{\omega}_{rw})\right)$.

Provided that ρ is chosen large enough to ensure sliding motion:

$$\rho > \eta + \left|f_i - \hat{f}_i\right| \tag{8}$$

where $\eta \in \mathbb{R}_+$.

Based on inequality (7) and (8) the η-reachability condition can be demonstrated:

$$e_i \dot{e}_i < -\eta |e_i| \tag{9}$$

The η-reachability condition (9) implies that $\boldsymbol{e} \to 0$ in a finite time. When $\boldsymbol{e}$ has converged to zero the sliding motion takes place and the following condition is met ([2]):

$$\dot{\boldsymbol{e}} = \boldsymbol{e} = \boldsymbol{0} \tag{10}$$

One of the disadvantages of the SMC is the chattering effect (high-frequency oscillations in the sliding mode control law) that can appear when the sliding surface is maintained. In order to avoid chattering, a pseudo-sliding function has been used [2], based on the sigmoid function:

$$\boldsymbol{\upsilon} = \rho \frac{(\boldsymbol{\omega} - \widehat{\boldsymbol{\omega}})}{\|(\boldsymbol{\omega} - \widehat{\boldsymbol{\omega}})\| + \varepsilon} \tag{11}$$

where ε is an arbitrarily small positive parameter, to avoid losing the SMO robustness, $\rho > 0$ is a gain, based on inequality (8), which must be large enough to ensure the sliding motion. Furthermore, the $\boldsymbol{\upsilon}$ numerical values are also called equivalent injection signals used to detect and isolate faults. The equivalent injection signals can be used to reconstruct faults or to estimate disturbance, as it will be shown in the next chapter.

A detailed observer model based on the Juventas satellite is provided in [1]. By replacing the pseudo-sliding function (11) in (3) the following observer can be obtained:

$$\dot{\widehat{\boldsymbol{\omega}}} = \boldsymbol{I}_s^{-1}\left[-\left(\widehat{\boldsymbol{\omega}} \times (\boldsymbol{I}_s \widehat{\boldsymbol{\omega}} + \boldsymbol{I}_{rw} \boldsymbol{\omega}_{rw})\right) + \boldsymbol{T}_c\right] + \boldsymbol{\upsilon} \tag{12}$$

The SMO from (12) is used to design the FDI system based on an innovative bank of observers by evaluating the equivalent injection signal. Seven SMOs are designed for different types of fault scenarios:

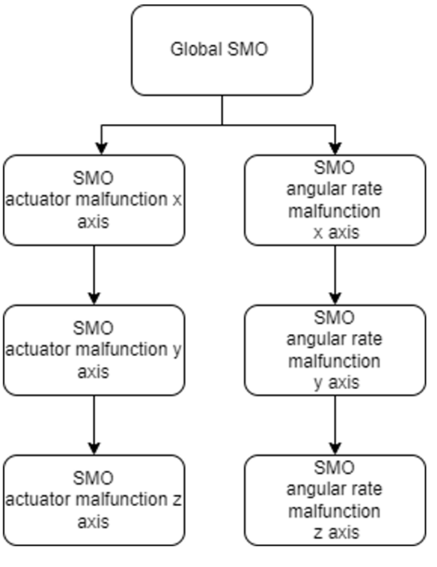

Fig. 1 – SMO bank, [1]

The global SMO is designed to work in normal conditions and detects preliminary anomalies that could occur in the attitude control systems. To detect possible faults the global SMO equivalent injection signal is evaluated and if it exceeds a predefined threshold a flag is raised. The global SMO will not provide detailed information about the fault type or isolation indications. The next step in the FDI SMO process is the evaluation of the remaining six SMO if the global SMO raised a flag. To detect and isolate the fault, the equivalent injection signals of the SMOs, designed for specific fault scenarios, are evaluated and the SMO that provides the minimum of the equivalent injection signal is the one that better models the fault. The SMO bank, Fig. 1, provides the possibility to isolate and detect faults for every actuator in part and gyroscope measurements. The information provided by the FDI SMO system can be used to perform fault reconstruction.

4. TORQUE RECONSTRUCTION

The actuator fault reconstruction is based on the FDI system from Fig.1 and the global SMO equivalent injection signal. The detection of fault type is crucial to perform correctly the reconstruction. The FDI SMO system is capable to provide information about the fault type, that can be used to reconstruct the fault. To perform the fault reconstruction, the equivalent injection signal error is used as proposed in [2] and [4].

In nominal conditions, the disturbance torque can be reconstructed. The disturbance reconstruction is done by assuming that the sliding motion of SMO defined in (10) has been established.

By replacing terms (1) and (12) in (5) the derivative error becomes:

$$\dot{\boldsymbol{e}} = \boldsymbol{I}_s^{-1}\left(-\boldsymbol{\omega} \times (\boldsymbol{I}_s\boldsymbol{\omega} + \boldsymbol{I}_{rw}\boldsymbol{\omega}_{rw}) + \widehat{\boldsymbol{\omega}} \times (\boldsymbol{I}_s\widehat{\boldsymbol{\omega}} + \boldsymbol{I}_{rw}\boldsymbol{\omega}_{rw})\right) + \boldsymbol{I}_s^{-1}\boldsymbol{T}_d - \boldsymbol{\upsilon} \tag{13}$$

During sliding motion, ensured when condition (10) is satisfied, the following equality will take place: $\boldsymbol{\omega} = \widehat{\boldsymbol{\omega}}$. In this hypothesis the equation (13) leads to:

$$\boldsymbol{0} = \boldsymbol{I}_s^{-1}\boldsymbol{T}_d - \boldsymbol{\upsilon} \tag{14}$$

In consequence, the disturbance can be estimated based on the equivalent injection signal when the system is working in nominal conditions:

$$\widehat{\boldsymbol{T}}_d = \boldsymbol{I}_s\boldsymbol{\upsilon} \tag{15}$$

The fault reconstruction is based on the complete fault of the actuator. The SMO will still receive as inputs the control torques from the control system without any faults. According to [1] the main disturbance torque acting on the satellite is the solar radiation pressure which is in order of ~ 10-6 Nm. By neglecting the disturbances equation and control torque (due to fault presence) equation (1) can be written in the following form:

$$\dot{\boldsymbol{\omega}} = \boldsymbol{I}_s^{-1}\left[-\left(\boldsymbol{\omega} \times (\boldsymbol{I}_s\boldsymbol{\omega} + \boldsymbol{I}_{rw}\boldsymbol{\omega}_{rw})\right)\right] \tag{16}$$

Further, by replacing the right-hand terms of (16) and (12) into (5) the derivative error becomes:

$$\dot{\boldsymbol{e}} = \boldsymbol{I}_s^{-1}\left(-\boldsymbol{\omega} \times (\boldsymbol{I}_s\boldsymbol{\omega} + \boldsymbol{I}_{rw}\boldsymbol{\omega}_{rw}) + \widehat{\boldsymbol{\omega}} \times (\boldsymbol{I}_s\widehat{\boldsymbol{\omega}} + \boldsymbol{I}_{rw}\boldsymbol{\omega}_{rw})\right) - \boldsymbol{I}_s^{-1}\boldsymbol{T}_c - \boldsymbol{\upsilon} \tag{17}$$

During sliding motion, ensured when condition (10) is satisfied, the following equality will take place: $\boldsymbol{\omega} = \widehat{\boldsymbol{\omega}}$. In this hypothesis, equation (17) leads to:

$$\boldsymbol{0} = -\boldsymbol{I}_s^{-1}\boldsymbol{T}_c - \boldsymbol{\upsilon} \tag{18}$$

The equivalent injection signal, when the system is working with actuator faults, is trying to compensate for the unexecuted control torque as follows:

$$\widehat{\boldsymbol{T}}_c = -\boldsymbol{I}_s\,\boldsymbol{\upsilon} \tag{19}$$

Therefore, equation (19) represents the actuator fault which is estimated based on the equivalent injection signal considering the assumption of complete actuator faults.

5. TORQUE RECONSTRUCTION CASE STUDY

The fault reconstruction based on FDI SMO is illustrated with a numerical case study for a 6U CubeSat with 12 kg mass. The main actuation system of Juventas is based on reaction wheels and thrusters are used for momentum dumping. The angular velocities of the Juventas satellite are measured by the MEMS gyroscope. The SMO configuration is: $\varepsilon = 0.01$ and $\rho = 0.01$.

The inertia tensor is derived considering information provided in [9], by considering the principal diagonal elements:

$$\boldsymbol{I_s} = \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix} \tag{20}$$

The mission profile and satellite general configuration are extracted from [9]. The sun acquisition phase is considered as per [1], where the solar panels are oriented towards the sun. The initial condition of the satellite's attitude considers a rotation with 20, 25 and 20 degrees with respect to the desired attitude. The first study case is the reconstruction of SRP disturbance torque based on (15). Fig. 2 presents the reconstruction of the SRP based on the injection error (orange line) with respect to the SRP generated with the Cannonball model (blue line).

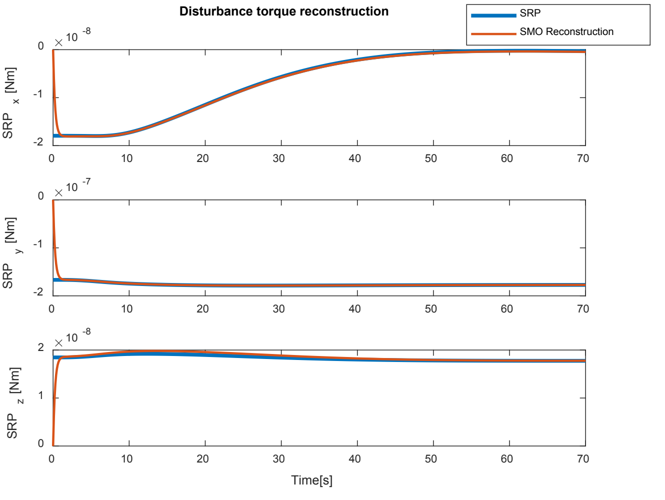

Fig. 2 – Disturbance torque reconstruction

The mean reconstruction absolute error (reconstructed SRP with respect to Cannonball SRP) is: 1.6379e-10 Nm on the x-axis with a standard deviation of 5.9720e-10 Nm , 5.4314e-10 Nm on the y-axis with a standard deviation of 5.6560e-09 Nm and 3.2980e-10 Nm on z-axis with a standard deviation of 6.3834e-10 Nm. The mean is computed after the sliding motion is ensured (in less than 2 seconds). As can be observed from Fig. 2, the reconstruction of the SRP is performed with good accuracy. The second study case is the reconstruction of the actuator fault modeled as a torque according to (19). The actuator fault reconstruction proposed in (19) is not limited to a certain type of actuator. For testing purposes, it is considered that the reaction wheel will not be able to execute the command torque. An actuator fault is applied to start with the second five of simulation first on the x-axis, secondly on the y-axis and finally on the z-axis in the satellite coordinate frame.

In Fig. 3 it can be noticed that the actuator fault on the x-axis is applied starting with second 5. The SMO can compensate for the fault by using the equivalent injection signal in 2 seconds. After the 7th second of the simulation, the sliding motion is achieved in a fault condition and the fault reconstruction can be performed considering equation (19). The torque reconstruction shows a mean absolute error of 1.5516e-05 Nm computed after sliding motion is achieved, with a standard deviation of 1.3961e-05 Nm.

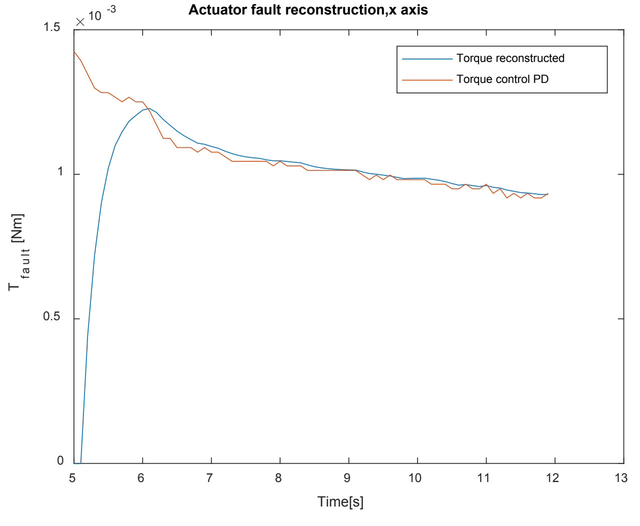

Fig. 3 – Actuator fault reconstruction, x-axis

In Fig. 4 it can be noticed that the actuator fault on the y-axis is applied starting with second 5. The SMO can compensate for the fault by using the equivalent injection signal in 3 seconds. After the 8th second of the simulation, the sliding motion is achieved in a fault condition and the fault reconstruction can be performed considering equation (19). The torque reconstruction shows a mean absolute error of 2.4326e-05 Nm computed after sliding motion is achieved, with a standard deviation of 1.2216e-05 Nm.

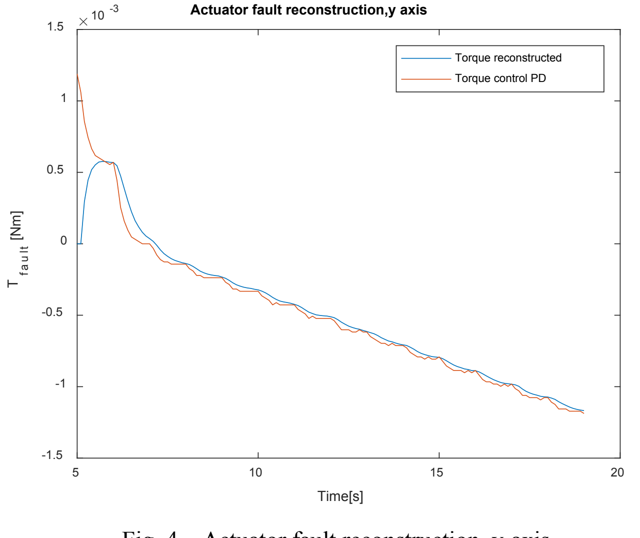

Fig. 4 – Actuator fault reconstruction, y-axis

In Fig. 5 it can be noticed that the actuator fault on the z-axis is applied starting with second 5. The SMO can compensate for the fault by using the equivalent injection signal in 2 seconds. After the 7th second of the simulation, the sliding motion is achieved in a fault condition and the fault reconstruction can be performed considering equation (19). The torque reconstruction shows a mean absolute error of 1.0351e-05 Nm computed after sliding motion is achieved. with a standard deviation of 9.1923e-06 Nm.

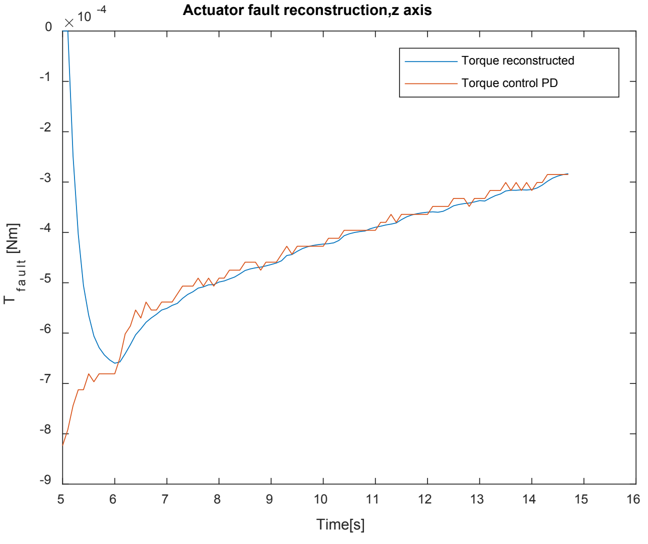

Fig. 5– Actuator fault reconstruction, z-axis

6. CONCLUSIONS

This paper presents an innovative FDI system based on a bank of SMOs considering satellite nonlinear dynamics. Each SMO is designed for different fault cases considering the actuation system or inertial measurement unit, [1]. The sliding mode function is based on a pseudo-sliding function to reduce the chattering effect. Based on the pseudo-sliding function the equivalent injection signal is used to reconstruct disturbances acting on the satellite or the fault.

The disturbance torque acting on the satellite is computed based on (15) by using the global SMO equivalent injection signal. The interpretation of (15) is valid in case no fault is present in the system. Moreover, in the case study has been observed that the reconstructed disturbance can be a sum of multiple factors acting on the satellite: external and internal disturbances, angular velocity measurement error, actuation precision of the command torque and even parametric uncertainties. Equation (15) will also contain modelling uncertainties. In consequence, in a real environment, the interpretation of (15) must be performed with caution. The study case presents the principle of disturbance reconstruction by using the SRP disturbance as a reference. The results show that SMO can reconstruct the SRP with high accuracy.

The actuator fault reconstruction is performed based on (19) by using the global SMO equivalent injection signal. The interpretation of (19) is valid through the information provided by FDI SMO when an actuator fault is detected. As in the case of disturbance reconstruction, the modelling uncertainties will be present in the actuator fault reconstruction, but due to the fault condition, the fault torque error will be higher than the modelling uncertainties. In consequence, the interpretation of (19) must be performed based on FDI SMO fault identification. The study case presents the principle of actuator fault reconstruction by simulating actuator faults. The results show that SMO can reconstruct the faults with high accuracy.

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