Satellites FDI system design using sliding mode observers

Florin-Adrian STANCU*[,1], Adrian-Mihail STOICA[1]

*Corresponding author
[1]Faculty of Aerospace Engineering, POLITEHNICA University Bucharest,
Splaiul Independentei 313, 060042, Bucharest, Romania,
stancu_florin_adrian@yahoo.com*, adrian.stoica@upb.ro

DOI: 10.13111/2066-8201.2022.14.1.16

Received: 10 November 2021/ Accepted: 18 January 2022/ Published: March 2022

Abstract: *This paper presents a fault detection and isolation system for the satellites attitude control. The fault detection and isolation system is based on an innovative bank of sliding mode observers, designed taking into account the satellite nonlinear dynamics. The observers are based on the sliding mode control theory, thus being robust to parametric uncertainties and bounded disturbances. A pseudo-sliding law is used to avoid the chattering effect and to reconstruct disturbances and faults based on equivalent injection signal. The bank of observers contains a total of seven sliding mode observers designed for different working scenarios. The first sliding mode observer is called the global observer and it is used to detect the fault appearance in the system, based on the equivalent injection signal. The other sliding mode observers are used to isolate and report any malfunction that may occur in the satellite's guidance and control unit. In order to reduce false alarms a mean window is used over the equivalent injection signal.*

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

1. INTRODUCTION

Nowadays, space missions become more complex, pushing spacecraft control systems to the limit. This phenomenon leads to the development and integration of new control systems and fault detection and isolation systems (FDI) that are more robust and efficient. One such ambitious mission is the European Space Agency's HERA planetary defense mission, which is part of the Asteroid Impact and Deflection Assessment to characterize a binary asteroid system named Didymos after the impact resulted during NASA DART mission, see Fig. 1.

HERA will be launched in 2024 and is expected to arrive in 2027 in order to characterize the impact crater. HERA will carry two 6U CubeSats named Juventas and APEX. The CubeSats will be deployed in the vicinity of Didymos binary system and will take higher risks during the mission. During the study case of the FDI the Juventas satellite, [2], 6U configuration is considered.

In this paper, an FDI system based on sliding mode observer (SMO) method is proposed. SMOs are based on sliding mode control (SMC) theory.

The SMC is suitable to control nonlinear dynamics when disturbances and uncertainties are present in the system.

The sliding mode FDI system is tested on a sun acquisition maneuver by using the dynamic and kinematic equations to model the satellite nonlinear dynamic. Quaternion form of kinematic equation is used to represent the spacecraft attitude. Solar radiation pressure disturbances are considered during simulation.

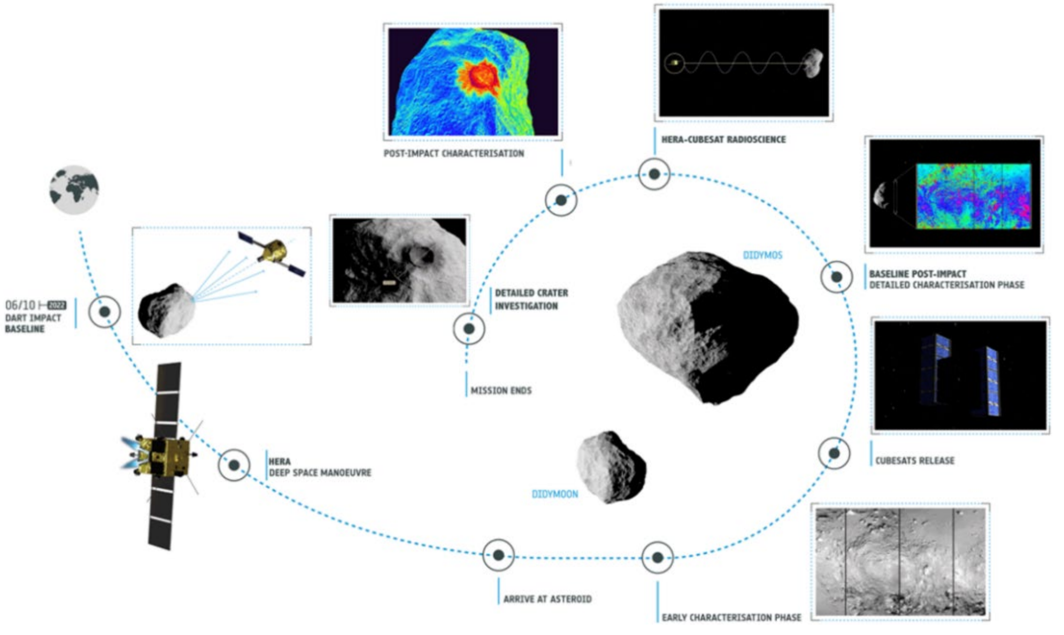

Fig. 1 – HERA Mission timeline (Credit: ESA, [1])

The SMO FDI relies on the evaluation of equivalent injection signal to detect and isolate the malfunction. Furthermore, based on the equivalent injection signal, the fault can be reconstructed.

In general, the sliding motion can be ensured by using signum control action to achieve best performances and robustness of the sliding mode observers, but chattering effect is present.

Based on the amplitude of the equivalent injection signal, a decision can be taken, by taking advantage of the fact that it gives information about reconstruction of fault signal.

Chattering is the effect caused by the high frequency oscillation along the sliding surface. In order to smooth the discontinuity generated by the signum function a continuous approximation based on the sigmoid function is proposed. This technique is named pseudo-sliding, due to the smoothed nature of the control action. The use of the continuous approximation function will decrease the robustness of the SMO, but in this paper it is shown that by properly tuning the sigmoid function good performances of the SMO can be achieved without affecting the estimated states in a drastic way.

The FDI SMO is based on an innovative bank of SMO designed for different malfunction cases.

2. SATELLITE DYNAMICS

In this paper the satellite is considered to be a rigid body with six degrees of freedom (DOF). The first three DOFs describe the translation of the satellite's center of mass, and the other three describe the rotational states around the satellite's center of mass.

The satellite attitude can be derived from dynamic and kinematic equations [3], which describe the rotational dynamics of the satellite subjected to internal or external torques. In accordance with [4] the satellite dynamics describe how the angular acceleration is affected by the effect of internal or external torques and the kinematics equations compute the satellite attitude based on its angular velocity.

The dynamics of a rigid spacecraft are derived from Euler's rotation equations and are defined by differential equations ([3]):

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

where $\boldsymbol{\omega}$ is the satellite angular velocity vector, $\boldsymbol{I}_s$ is the satellite's inertia tensor, $\boldsymbol{I}_{rw}$ is the reaction wheels inertia tensor, $\boldsymbol{\omega}_{rw}$ is the reaction wheels angular velocity vector, $\boldsymbol{T}_{ext}$ are the external disturbance torques acting on the satellite and $\boldsymbol{T}_c$ is the control torque generated by the reaction wheels.

The kinematic equations of the satellite depict the satellite's attitude in a quaternion form by describing the relation between the attitude and the satellite angular speed in body frame. These set of equations are defined as first-order differential equations as per [5]:

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

where $\otimes$ denotes quaternion product.

In the literature there are a multitude of alternatives to kinematic equation caused by the quaternion and triad convention. A detailed explanation of the kinematic equation form based on different convention is provided in [5].

In this paper, the following quaternion convention is considered with q_s being the scalar part:

$$\boldsymbol{q} = \begin{bmatrix}q_s\\ q_x\\ q_y\\ q_z\end{bmatrix} \tag{3}$$

For FDI testing purposes, a representative simulator has to be developed that can ensure the desired attitude control in nominal scenarios when faults are not present in the system. Designing attitude control systems is a complex but fundamentally necessary task to properly test an FDI system. Consequently, an attitude control system with the following functionalities has been designed :

- PD controller – to ensure the necessary torque based on attitude error and satellite angular velocity,
- Actuator model - containing representative figures of the real reaction wheel to model as closely as possible the actuator behavior and performances,
- Satellite model – based on dynamic and kinematic equations of motion,
- Reaction wheel momentum dumping – for cases when the flywheel reaches its maximum velocity,
- Solar radiation pressure model – modeled as cannonball, [6], simplified model to generate representative disturbance torque,
- FDI based on the SMO bank observers.

Fig. 2 presents the work flow of the attitude control system considering the FDI system as well:

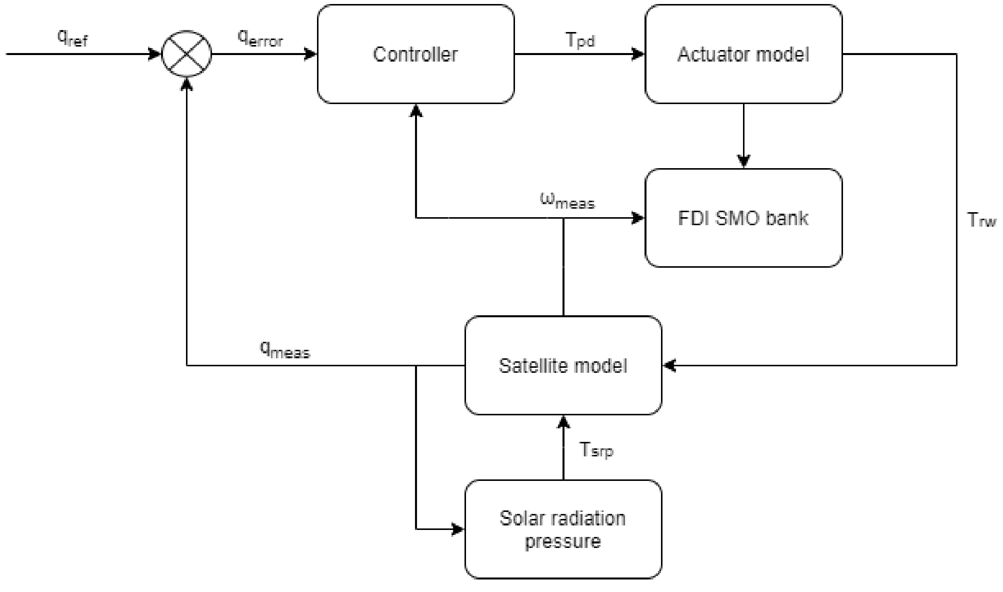

Fig. 2 – Attitude control system and FDI system architecture

In Fig. 2 the quaternion error is represented by the following equation ([5]):

$$\boldsymbol{q}_{error} = \boldsymbol{q}_{ref} \otimes \boldsymbol{q}^{*}_{meas} \tag{4}$$

where by "*" is denoted the quaternion conjugate.

3. FDI DESIGN USING SMO

FDI review from [7] describes two general ways of the FDI design methods based on hardware and analytical redundancy, respectively. The concept of hardware redundancy is the simplest concept of FDI and it is based on accommodating redundant measurement units into the satellite architecture. The concept is to evaluate the measurement of all the sensors and compare them against each other. This technique implies to have two or three redundant sensors onboard. Even though this technique is reliable it has some major disadvantages in aerospace industry, namely :

- increase of the satellite mass,
- use of additional space in the satellite configuration that could be used for other payloads,
- increase of power consumption.

The second approach is the analytical redundancy which is based on mathematical models. The use of FDI based on mathematical models opens the possibility of designing complex FDI systems using various techniques, like: state observers, Kalman filters, artificial intelligence, etc. The concept of analytical redundancy is to make decision based on the mathematical model, such as: evaluation of residuals or reconstruction of parameters based on model inputs and outputs. In order to use mathematical models, the dynamic model of the satellite must be known. Usually, a perfect mathematical model is not known, due to parametric uncertainties and unknown disturbances. In order to cope with this, the selected model of design has to be carefully selected taking into account the mission needs. A detailed tradeoff for various FDI systems techniques using analytical redundancy can be found in [7]. The advantages of analytical redundancy are:

- reduction of the satellite mass,
- lack of need for additional hardware,
- possibility to develop complex FDI.

In this paper an FDI using mathematical model is proposed to be developed around dedicated SMO. The satellite dynamic includes nonlinearities which are combined with parametric uncertainties and unmodeled disturbances. In order to cope with this complex dynamics an FDI based on SMO is proposed. The SMO, being based on SMC theory, will inherit SMC performances and robustness. The SMC is a robust type of nonlinear control law specifically designed to overcome control issues encountered in nonlinear systems. The SMC is designed to force the system states to fall on a predesigned surface in the state space domain. This surface is commonly known as sliding surface. As soon as the sliding motion has been established, the SMC will maintain the states along the sliding surface [7]. The selection of the sliding surface is of great importance depending on the intended application. One of the common sliding surface is the signum function which causes the chattering effect. In case of control problems, chattering is not desirable because the high frequency zero crossing could damage the actuator in an irreversible way. The SMO will inherit the chattering effect if the signum function is used. The chattering effect can be reduced by using sliding functions carefully designed to smooth the high frequency oscillations. The usage of such special sliding function can affect the robustness of the sliding mode method. In comparison with classic estimator the SMO will follow the states of the real system when bounded disturbances and uncertainties are present. This is the main reason why SMO-based residues are not used, thus the equivalent injection signal is considered, being the signals where differences can be observed in case of malfunctions. In this paper, a nonlinear system dynamics defined in [8] is considered as basic formulation of a nonlinear state space model:

$$\begin{gathered}\dot{\boldsymbol{x}}(t) = f(\boldsymbol{x}(t)) + \boldsymbol{B}\boldsymbol{u}(t) \\ \boldsymbol{y}(t) = h(\boldsymbol{x}(t))\end{gathered} \tag{5}$$

where : $\boldsymbol{x} \in \boldsymbol{R}^n$ are the system states vector, f and h are nonlinear function, $\boldsymbol{B}$ control matrix, $\boldsymbol{u} \in \boldsymbol{R}^m$ is control input, $\boldsymbol{y} \in \boldsymbol{R}^p$ is output vector.

Taking into consideration that this paper targets a satellite dynamic, equations (1) and (2) are written in the nonlinear state space representation defined in (5):

$$\begin{gathered}\dot{\boldsymbol{\omega}}(t) = f(\boldsymbol{\omega}(t)) + \boldsymbol{B}\boldsymbol{u}(t) \\ \boldsymbol{y}(t) = \boldsymbol{C}(\boldsymbol{\omega}(t))\end{gathered} \tag{6}$$

where $\boldsymbol{C}$ is the measurement matrix and f is defined taking into account the terms of equation (1):

$$f(\boldsymbol{\omega}) = -\boldsymbol{I}_s^{-1}\big(\boldsymbol{\omega} \times (\boldsymbol{I}_s\boldsymbol{\omega} + \boldsymbol{I}_{rw}\boldsymbol{\omega}_{rw})\big) \tag{7}$$

According to [8] the sliding mode observer is similar to the linear observer, with the replacement of the sliding mode function. The SMO is defined based on the state space representation defined in (6) as follows:

$$\begin{gathered}\dot{\hat{\boldsymbol{\omega}}}(t) = f\big(\hat{\boldsymbol{\omega}}(t)\big) + \boldsymbol{B}\boldsymbol{u}(t) + \boldsymbol{v} \\ \hat{\boldsymbol{y}}(t) = \boldsymbol{C}(\hat{\boldsymbol{\omega}}(t))\end{gathered} \tag{8}$$

where by “^” is denoted the estimation and $\boldsymbol{v}$ is the sliding mode function.

The sliding mode function $\boldsymbol{\upsilon}$ is of great importance for the SMO performances. The output of $\boldsymbol{\upsilon}$ is the so-called equivalent injection signal used to detect and isolate faults. The equivalent injection signal contains useful information regarding disturbances, uncertainties and unknowns that affect the system. Because of this, the equivalent injection signal can be used to reconstruct the fault.

As mentioned above the simplest sliding mode function that can be defined is the signum function that is also proposed in [8]. The chattering effect is not a critical issue for the SMO FDI as it is designed to run in software.

However, it is desirable to have a smooth equivalent injection signal that can be easily interpreted and have a physical meaning. In order to avoid the chattering effect, a pseudo-sliding function is proposed [9]. The pseudo-sliding function is defined in such a way to smooth the discontinuities and still ensure the sliding motion. One of the best function candidate is identified in [9] as being the sigmoid function, Fig. 3.

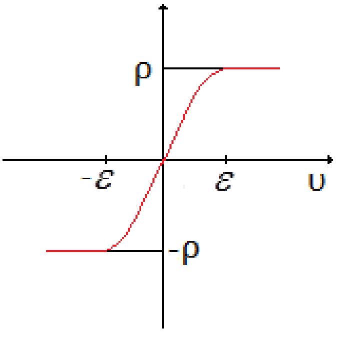

Fig. 3 – Pseudo-sliding function

Considering system (8) the following pseudo-sliding function is defined:

$$\boldsymbol{\upsilon} = \rho \frac{(\boldsymbol{y}(t) - \hat{\boldsymbol{y}}(t))}{\|(\boldsymbol{y}(t) - \hat{\boldsymbol{y}}(t))\| + \varepsilon} \tag{9}$$

where ρ is a gain large enough to maintain sliding motion and ε shall be a positive number with the condition $\varepsilon \approx 0$, large values of ε will decrease the robustenss of the observer due to high smoothing effect. ε is chosen as a tradeoff between required performances and smoothing action [9].

The SMO described in (8) is used to design an innovative bank of observers used to detect, report and isolate faults, based on the evaluation of the equivalent injection signals. The SMO bank is composed by seven estimators as depicted in Fig. 4, each one designed for a certain scenario.

The observer bank contains a global SMO that is designed to work in normal conditions. Three SMOs are designed to model reaction wheels malfunctions. For every axis in part, a specific SMO is designed for the malfunction case. The last three SMOs are designed to model gyroscope malfunctions.

As in case of actuators, for every axis in part, a specific SMO is designed for the gyroscope malfunction case. The global SMO is in charge to detect the malfunction without being able to isolate it by evaluating the equivalent injection amplitude.

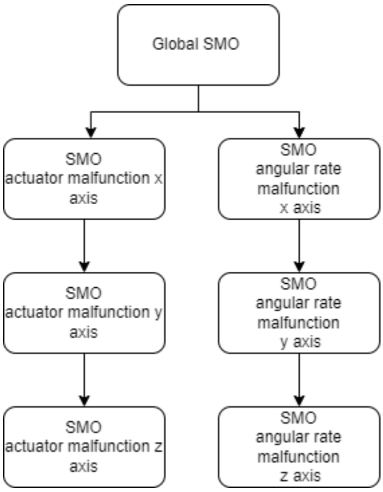

Fig. 4 – FDI SMO bank

Table 1 – FDI SMO bank parameters

SMO	B	C	ε	ρ
Global SMO	$\begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix}$	$\begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix}$	0.01	0.001
SMO actuator malfunction x	$\begin{bmatrix}0&0&0\\0&1&0\\0&0&1\end{bmatrix}$	$\begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix}$	0.01	0.001
SMO actuator malfunction y	$\begin{bmatrix}1&0&0\\0&0&0\\0&0&1\end{bmatrix}$	$\begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix}$	0.01	0.001
SMO actuator malfunction z	$\begin{bmatrix}1&0&0\\0&1&0\\0&0&0\end{bmatrix}$	$\begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix}$	0.01	0.001
SMO angular rate x	$\begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix}$	$\begin{bmatrix}0&0&0\\0&1&0\\0&0&1\end{bmatrix}$	0.01	0.001
SMO angular rate y	$\begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix}$	$\begin{bmatrix}1&0&0\\0&0&0\\0&0&1\end{bmatrix}$	0.01	0.001
SMO angular rate z	$\begin{bmatrix}1&0&0\\0&1&0\\0&0&1\end{bmatrix}$	$\begin{bmatrix}1&0&0\\0&1&0\\0&0&0\end{bmatrix}$	0.01	0.001

4. FDI SMO DETECTION AND ISOLATION

The main objective of the FDI system is to raise an alarm when a fault or malfunction is detected and to identify the source. This paper presents a FDI scheme, based on SMO for the satellite attitude control system. The proposed FDI SMO system is based on the architecture proposed in Fig. 4, where the global SMO is in charge to preliminary detect any anomalies found in the systems. In order to do this the equivalent injection signal of the global SMO is evaluated. When the equivalent injection signal amplitude exceeds a FDI threshold, a preliminary flag is triggered. The role of the global SMO is well defined, being in charge only to detect a possible fault without any detailed information about the fault or its source. In order to reduce false alarms, a mobile mean window is applied on the equivalent injection signal.

$$\boldsymbol{v}_m = \frac{1}{n}\sum_{w}^{w+n} \boldsymbol{v}_w \quad (10)$$

where w represents the start of the window, $w+n$ represents the end of window and n is the number of samples.

In this paper, in order to facilitate the fault interpretation, we chose to reconstruct the injection error as a torque, due to the following advantages:

- the FDI threshold is defined as a torque,
- the torque has physical significance,
- the reconstructed torque can be compared with the disturbance torque.

The initial detection is performed, considering the following logic:

$$\boldsymbol{v}_m > p \quad (11)$$

where p is FDI threshold.

After a fault is detected, the isolation procedure starts. All six SMOs designed for different malfunction cases are evaluated. The injection error signals are evaluated in order to detect the observer that better replicates the malfunction by detecting the minimum of the equivalent injection signal error:

$$\boldsymbol{v}_{\min} = \min_{i=1,\dots,N}(abs(\boldsymbol{v}_i)) \quad (12)$$

where $\boldsymbol{v}_i$ denotes the equivalent injection signal of the observer i and N is the number of considered observers. The isolation of the fault is proposed to be performed in order to give the possibility to take recovery actions. The $\boldsymbol{v}_{\min}$ is followed in a predefined sized mobile window (5 seconds considered in this paper) and if an observer flag is raised without any interruptions in this period of time, the fault is declared and the isolation is performed considering the observer flag.

5. FDI SMO CASE STUDY

The proposed FDI SMO design methodology is illustrated by numerical case studies taking as reference HERA CubeSat mission. In [11] the 6U CubeSat mission is detailed with a clear explanations of all the phases that are considering during the mission, from the satellite commission phase until the landing on Didymoon. Furthermore, the satellite general configuration and properties are extracted from [11] to be modeled into the simulation, in order to increase representativeness of the test. From the mission trajectory perspective, representative information is extracted from HERA SPICE kernels [10]. The scenario considered in this paper is a sun acquisition, where the solar panels have to be oriented towards the sun to generate the necessary energy to ensure nominal working of the satellite units.

Table 2 – Study case conditions

Condition	**Value**
CubeSat dimension	6U
CubeSat mass	12 [kg]

Distance with respect to sun	~1.4 [AU]
Initial attitude	XYZ rotation with 20, 25 and respectively 20 degrees with respect to desired attitude
Gyroscope noise	~ 10^{-4} [rad/s]
Torque SRP	~ 10^{-6} [Nm]
Equivalent injection threshold	10^{-4} [Nm]

The first case study shows the nominal behavior of the attitude control system without any error, as shown in Fig. 5. The simulation shows that the desired attitude is reached by using a PD controller in almost 100 s. During this case, no FDI flag is raised, which is expected due to the fact that no fault has been inserted. The results of the study case considering the malfunctions of the actuator and angular speed measurement unit are presented in Table 3. The time of the fault occurrence is simulated by considering the malfunctions of the actuators or sensors from this moment. In order to detect the fault, the FDI SMO will perform the initial detection after a number of seconds, called time taken for initial detection, see Table 3, which is computed with respect to the time of the fault occurrence. Finally, the time taken for the fault reporting and isolation, see Table 3, is computed with respect to the time of the fault occurrence. The FDI SMO is rising flags when a fault is detected. Every SMO, from the bank, has its own unique index, for identification purposes. The FDI SMO flag is raised when a fault is detected and isolated based on the index associated with the SMO index. In this way the fault isolation is performed.

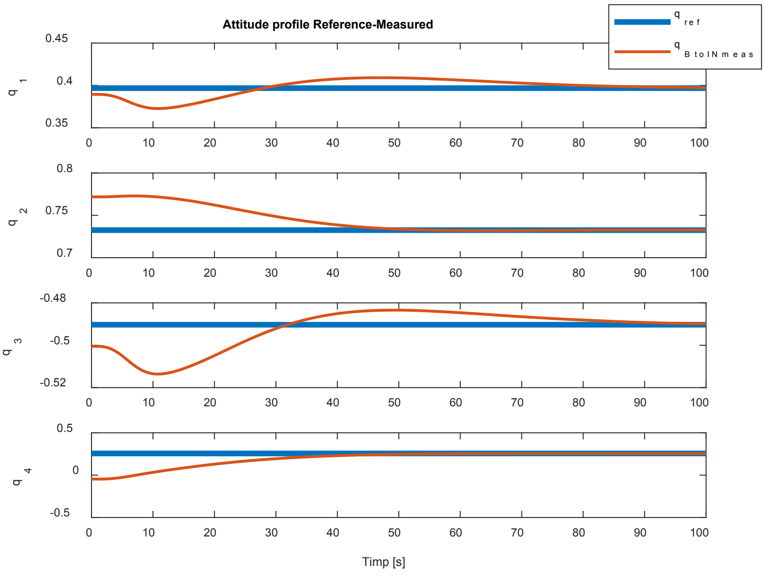

Fig. 5 – Satellite attitude

Table 3 – Study case results

Case N/o.	Fault Type	Time of appearance [s]	Time taken for initial detection [s]	Time taken from declaration and isolation [s]
1	Actuator fault x axis	5	8	13
2	Actuator fault x axis	50	20	25
3	Actuator fault y axis	5	15	20

4	Actuator fault z axis	5	13	18
5	Gyroscope fault x axis	10	4	9
6	Gyroscope fault y axis	10	11	16
7	Gyroscope fault z axis	10	6	11

In Table 3 it can be observed that different cases of faults are simulated for both the actuator and the gyroscope. Different time of fault occurrences are evaluated in order to evaluate FDI SMO performances.

The FDI SMO initial detection is different from case to case, depending on the amplitude of the changes that are present in the system. After the initial declaration, the FDI SMO will evaluate the equivalent injection signal for another five seconds before declaration and isolation. It can be noticed that if the fault occurs at the beginning of the maneuver, when the PD control will generate bigger changes into the system, the initial detection is performed faster.

By evaluating case 1 and case 2, it can be observed that the fault will occur at different times. In case 1, the fault occurs at the beginning of the maneuver when the FDI SMO is capable to detect and isolate the fault in 13 seconds. In case 2, the fault occurs after 50 seconds of the maneuver and by evaluating Fig. 5 it can be noticed that it is required less torque into the system to achieve the reference attitude (due to less attitude error between the measured attitude and the reference attitude). The results is that the changes into the system are smaller and the equivalent injection signal will increase slower. The final results is a delay in reporting and isolation of the fault.

6. CONCLUSIONS

This paper presents a robust FDI system for satellite nonlinear dynamics. The FDI is based on the sliding mode observers by taking advantages of the sliding mode method robustness to bounded disturbances and uncertainties. The chattering effect is avoided by implementing a continuous approximation based on the sigmoid function, called pseudo-sliding. The detection and isolation is done based on equivalent injection signal and thanks to pseudo-sliding approximation the fault signal reconstruction is possible. The FDI SMO is based on an innovative SMOs bank of observers, each observer being designed for different actuators and measurement units faults. A total of seven SMOs are used, where the global estimator is the master that performs the initial detection.

The equivalent injection signal is filtered using a mobile window mean to reduce false alarms. An important aspect is that the detection time varies with the amplitude of the changes that are present in the system. For the fault reporting and isolation purpose, the other six SMOs equivalent injection signals are evaluated. A study case on a 6U CubeSat and thresholding/tuning of SMOs has been performed taking into account the mission profile to reduce at minimum the false alarms. The FDI SMO proved to be able to accurately detect and isolate the faults.

ACKNOWLEDGEMENT

This article is an extension of the paper presented at ***The 39th "Caius Iacob" Conference on Fluid Mechanics and its Technical Applications***, 28 – 29 October 2021, Bucharest, Romania, Virtual Conference, Section 3 – Dynamical Systems.

REFERENCES

[1] * * * *HERA Mission timeline*, accessed 07/11/2021: https://www.esa.int
[2] H. R. Goldberg, Ö. Karatekin, B. Ritter, A. Herique, P. Tortora, C. Prioroc, B. G. Gutierrez, P. Martino, I. Carnelli, *The Juventas CubeSat in Support of ESA's Hera Mission to the Asteroid Didymos,* 33rd Annual AIAA/USU Conference of Small Satellites, *SSC19-WKIV-05.*
[3] J. R. Wertz, *Spacecraft Attitude Determination and Control*, Kluwer Academic Publishers, Reprinted 1980, 1984, 1985 1986, 1988,1990.
[4] R. Izadi-Zamanabadi, R. Wisniewski, D. R. Pedersen, J. D. Grunnet, J. A. Larsen, K. K. Laursen, E. Kolakowska, I. P. Amo, *Attitude Control Systems for AAUSAT-II*, IAS8 2004.
[5] E. Fresk, G. Nikolakopoulos*, Full Quaternion Based Attitude Control for a Quadrotor*, European Control Conference, 2013.
[6] P. W. Kenneally, *High Geometric Fidelity Solar Radiation Pressure Modeling via Graphics Processing Unit*, 2010.
[7] I. Nagesh, *Fault diagnosis for a satellite system using sliding mode observers*, 2015.
[8] S. Drakunov, V. Utkin, *Sliding Mode Observers. Tutorial*, Proceedings of the 34th Conference on Decision & Control, New Orleans, 1995.
[9] C. Edwards, S. K. Spurgeon, *Sliding Mode Control Theory and Applications*, Taylor & Francis Group, 1998.
[10] * * * *HERA SPICE kernels*, accessed on 09/2021: https://www.cosmos.esa.int/web/spice/spice-for-hera
[11] H. Guillaume, V. Guillaume, *A study of the landing phase of the Juventas CubeSat on the moon of the binary asteroid system Didymos*, 2019-2020.