VARIABLE FAULT DETECTION AND ISOLATION THRESHOLD BASED ON SLIDING MODE OBSERVERS

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This paper presents a variable detection threshold strategy for a satellite fault detection and isolation (FDI) system based on a sliding mode observer (SMO) approach. The FDI system is using an innovative bank of SMOs designed for different fault scenarios cases. The equivalent injection signal is influenced by the amplitude of uncertainties and disturbances due to its nature to counter these unknowns. For a general maneuver, this behavior is present, so to enhance and reduce fault detection time, a variable FDI threshold is proposed. The variable FDI threshold is modeled as a parabola plane curve.

Keywords: variable threshold, sliding mode observers, fault detection and isolation, pseudo-sliding, equivalent injection signal, CubeSat.

1. Introduction

Nowadays the FDI systems used in the space sector is mainly relying on hardware (HW) redundancy. This solution implies increasing the satellite mass and volume due to the need for redundant sensors and actuators. In space missions, the mass budget is very limited and due to the high cost of a space vehicle is desirable to get the most out of the satellite. One solution is to design a new FDI system based on a mathematical model and reduce to a minimum the redundant components. In this configuration, the redundant components can be substituted with devices that can contribute to increase the scientific return of the mission. This paper presents an FDI system design based on SMO, which is in the category of model-based FDI.

HERA is a planetary defense mission [3], with the objective of investigating the Didymos system. HERA spacecraft will travel with two CubeSats designed to take more risks in the mission. Juventas [4], is one of the satellites and is considered as a study case in this paper, for which an innovative FDI design based on SMOs using nonlinear dynamics is proposed. The observer configuration is based on the theoretic developments presented in [5] and [6] and is using the equivalent injection signal to detect and isolate faults. The FDI SMO is designed around a bank of SMOs which is using a continuous approximation function called pseudo-sliding [1]. The pseudo-sliding motion avoids the chattering effect, caused by the use of the signum

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function, and it provides a smoothed equivalent injection signal. Furthermore, as shown in [2] by using the pseudo-sliding motion concept the disturbances or faults can be reconstructed. The bank of observers is composed of seven SMOs, the first one being the global SMO used to detect the fault and the remaining ones are used for isolation, designed considering gyroscope and actuators faults scenarios, as detailed in [1].

The main advantage of the presented FDI SMO system is the robustness of the observers' bank to dynamic uncertainties and disturbances. Furthermore, the innovative hybrid design of the FDI SMO system, detailed in chapter 3, reduces to a minimum the false fault detection and isolation. This paper focuses on the design of a variable FDI threshold that improves significantly the FDI SMO performances by reducing the false fault detection and fault detection time.

2. Sliding Mode Observer for FDI

The main purpose of the FDI system, presented in this paper, is to detect and isolate faults by reducing false fault detection alarms. The SMO is designed to force the state to fall and maintain them around a predesigned sliding surface. The design of the sliding surface and the reachability condition are detailed in [1] and [2]. The SMO design inherits the robustness to dynamic uncertainties and disturbances from the sliding mode theory.

According to [1] and [2] the SMO has the following form (being based on general Utkin observer [5], applied for satellite dynamics [6]):

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

where $\hat{\boldsymbol{\omega}}$ is the estimated 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 torque vector acting on the satellite and $\boldsymbol{T}_c$ is the command torque vector. $\boldsymbol{\upsilon}$ represents the injection signal modeled as a pseudo sliding function:

$$\boldsymbol{\upsilon} = \rho\frac{(\boldsymbol{\omega}-\hat{\boldsymbol{\omega}})}{\|\boldsymbol{\omega}-\hat{\boldsymbol{\omega}}\|+\varepsilon} \tag{2}$$

where $\varepsilon \approx 0$, is a positive small number to avoid losing the SMO robustness and ρ is a gain large enough to ensure the sliding motion. The $\boldsymbol{\upsilon}$ term is used to avoid the chattering effect which occurs when the sliding surface is maintained and to directly obtain the equivalent injection signal, without any additional low pass filtering. A detailed analysis regarding the stability of the observer presented in (1) may be found in [2], being based on η-reachability condition. The analysis shows that the term ρ must be selected large enough, considering the bounded dynamics uncertainties and external disturbances, to ensure the sliding motion. As shown in [2] for a large value of ρ the SMO becomes robust to uncertainties and disturbances and therefore the injection signal ensures that the observer error $\boldsymbol{\omega} - \hat{\boldsymbol{\omega}}$ tends to zero in a finite time. This means that in a finite time, the residue of angular velocity will tend in the vicinity of zero in the presence of bounded disturbances and uncertainties, so the residue of angular velocity cannot be used for fault detection. This is a particularity of the SMO compared to classical observers. To take advantage of the SMO robustness in FDI designs, in [7] is proposed to use the equivalent injection signal to declare faults. This approach is used in this paper where the $\boldsymbol{\upsilon}$ term is used to declare and isolate faults.

3. Fault Detection and Isolation using Sliding Mode Observer

In comparison with FDI schemes which use classical observers to compute the state residues for fault detection, the FDI based on sliding mode observers uses the equivalent injection signal. The robustness of the SMO provides the possibility to perform disturbances and faults reconstructions based on the equivalent injection signal, during sliding motion. The reconstruction approach can be found in [2], where it was also shown that the reconstruction of disturbances or faults can be performed with high accuracy. Considering these results, the current FDI SMO is using, for the detection and isolation, the equivalent torque, computed based on the equivalent injection signal:

$$\boldsymbol{T}_{ech} = \boldsymbol{I}_s \boldsymbol{\upsilon} \tag{3}$$

It must be mentioned that the equivalent torque is obtained using the reconstruction approach presented in [2], with the remark that during the sliding motion reaching phase the equivalent torque does not represent a reconstruction of a fault or disturbance. In this hypothesis the equivalent torque is seen as the necessary energy to be introduced in the system to reach and maintain the sliding motion.

The FDI SMO system, proposed in this paper, is based on a hybrid approach that uses a SMOs bank to detect and isolate the malfunction and a gyroscope monitoring functionality that provides information to the FDI system to better isolate the fault. The SMO bank configuration is widely described in [1] and consists of one Global SMO designed to work in nominal conditions, 3 SMOs designed for actuator faults scenarios and finally the last 3 SMOs designed for angular measurement units' faults scenarios. The observers design considering the fault scenarios are grouped in the Isolation SMO block, as shown in Fig.1. The following fault scenarios are considered: actuator fault scenarios (one for every axis in part), gyroscope fault scenarios (one for every axis in part) and frozen gyroscope measurements.

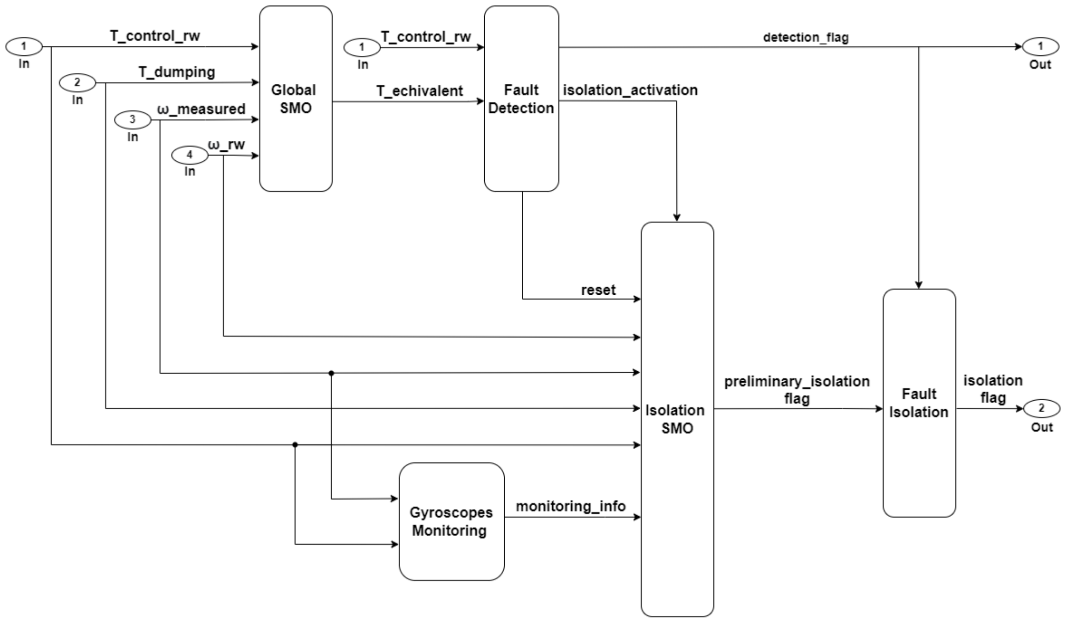

Fig. 1. FDI SMO detailed architecture

The Global SMO is designed to work without interruptions and can only provide information regarding fault detection. The Fault Detection block has multiple functionalities, among which is using Global SMO information to declare a possible fault, by tracking the equivalent torque mean (mean computed over a window of 2 seconds, using a circular buffer, $\boldsymbol{T}_{echm}$) and compute the variable thresholds, p_{ech}, based on command torque. A fault declaration is done only if the Global SMO reached the sliding motion beforehand and if $\boldsymbol{T}_{echm}$ is higher than p_{ech} , for details see [1]. The Fault Detection block controls the isolation bank by activating and restarting it if a preliminary fault detection is flagged. The initial condition of the sliding mode observers from Isolation SMO block is computed based on the mean of the last measurement of the angular velocities performed over 2 seconds.

The Gyroscopes Monitoring block is tracking the angular velocities measurements and has an informative functionality, without declaring or isolating faults. The functionalities of Gyroscopes Monitoring block are:

- Give information about isolation feasibility. In case if the angular velocities of the satellite are small the isolation cannot be performed.

- Provides information about frozen gyroscope, by following the measurements of the gyroscope over 2 seconds.
- Approximate the measured angular velocities profiles, on a small interval (2 seconds), with a linear regression using the least square method. If the residue measured angular velocities and estimated angular velocities using linear regression is bigger than a predefined threshold, at least one time, then the information is sent to the Isolation SMO block (to use the isolation observers designed for gyroscope malfunction scenarios). In case no information about high residue is provided, then the Isolation SMO block will use the actuator malfunction scenarios.

The main functionality of the Isolation SMO block is to run the isolation bank and perform preliminary fault isolation. The isolation using SMO is based on detecting the observer that provides the minimum equivalent torque, as detailed in [1]. The minimum equivalent torque, which is based on the equivalent injection signal, corresponds to the observer that better maps the fault scenario. This information is enough to isolate the fault and is formally called preliminary isolation information. The preliminary isolation information is a flag, where its value represents an insolation code: 0 no fault, 1-3 actuator fault, 4-6 gyroscope fault and 7 gyroscope frozen measurement. Finally, the Isolation SMO block can provide insolation information about actuators malfunction, gyroscope malfunction, frozen gyroscope, and isolation non-feasibility.

The Fault Isolation block is tracking if the preliminary isolation flag is maintained at least 5 seconds before declaring any isolation. It is also checking if the isolation estimator that is preliminarily isolated is in the sliding motion. Finally, it is declaring the isolation as a flag, where its value represents an insolation code pointing the fault type (codes meaning being identical with the ones of preliminary isolation information).

3. Variable FDI Threshold

In this paper is proposed a variable FDI threshold for satellite maneuver with the objective to improve the detection time in the last part of the maneuver, the moment when the angular velocities of the satellite are small, Fig. 3. Also, the benefit of a variable threshold is visible when dynamic uncertainties are taken into account. By evaluating (1) is clear that the dynamic uncertainties will have a direct impact on the amplitude of the equivalent injection signal. The effect is that during the incipient phases of the maneuver, when satellite angular velocities are higher, the equivalent injection signal will show higher values. In the final part of the maneuver, when the satellite angular velocities are smaller, the effect of dynamic uncertainties over the equivalent injection signal is reduced. Consequently, if a fix high threshold is maintained during the last phase of the maneuver the detection of a possible fault is delayed by a considerable amount of time (time until the malfunction will propagate in the system and become detectable by the high threshold). This paper effort is concentrated on reducing this undesired effect to a minimum, by proposing a variable FDI threshold based on the command torque. The most natural candidate based on which the variable threshold could be computed is the measured angular velocity of the satellite. However, in the presence of a gyroscope fault the variable threshold will be computed incorrectly, so the command torque is considered instead. The decision is based on the proportional-derivative (PD) controller which uses the attitude and the angular velocity to compute the command torque.

The dependency profile between the command torque and the variable threshold is also important. The first candidate is to use a linear dependency, but it is noticed that parabolic dependency is better since it allows a high threshold during the incipient part of the maneuver and favors the low threshold in the last part of the maneuver when the angular velocities are low. Based on this consideration the following FDI threshold profile has been adopted:

$$(x-h)^2 = 4f(y-k) \tag{4}$$

where: x and y are cartesian coordinates, (h,k) is the parabola vertex, $4f$ is the length of latus rectum. The design of the variable is bounded by a superior and inferior threshold. The superior threshold is correlated with the maximum control torque (in accordance with actuator performances, [8]) and represents the vertex of the parabola. The inferior threshold is the minimum value that the variable threshold can take, being an arbitrary threshold, set by simulation. The rate of change of the variable threshold with the control torque is manipulated by the focus value (set by the f term).

The variable threshold profiles are constructed considering a maximum dynamic uncertainty over $\boldsymbol{I_s}$ of 20% and are bounded by a minimum and maximum threshold. It is common in the FDI design to choose detection thresholds by extensive analysis, so the simulator prepared to test the FDI SMO system, detailed in [1], is used to establish the maximum and minimum thresholds.

The variable threshold profile for equivalent torque, p_{ech}, is proposed to be designed by using the following parameters:

Table 1

Variable threshold design for equivalent torque

Parameters	Value
p_{ech}(superior)	$3.5 \cdot 10^{-4}[Nm]$
p_{ech}(inferior)	$0.5 \cdot 10^{-4}[Nm]$
T_r(maximum,[8])	$1.5 \cdot 10^{-3}[Nm]$
f	-0.0018

The following profile of the variable equivalent torque threshold is obtained by considering parameters presented in Table 1:

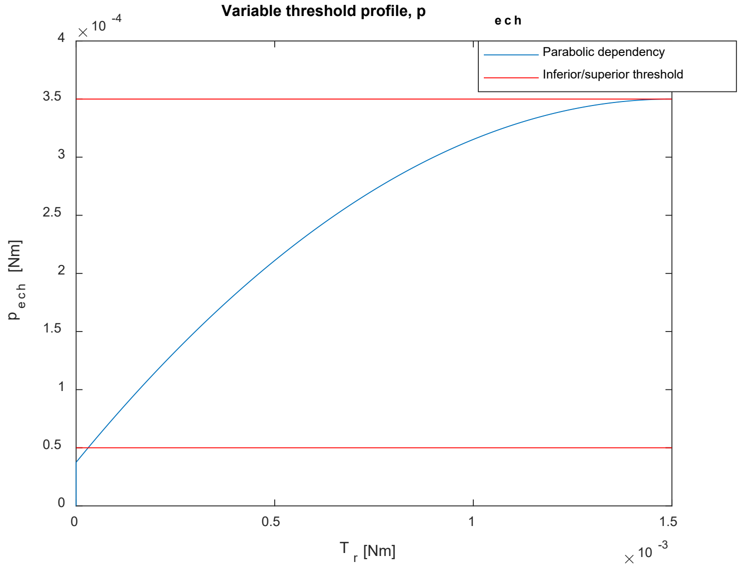

Fig. 2. Equivalent torque variable threshold profile

A case study using the Juventas CubeSat configuration is conducted considering a sun acquisition maneuver, as described in [1] and [2] by activating gyroscope noise and sun radiation pressure disturbance. In the following figure the attitude and angular velocities profiles during a maneuver without any fault are presented:

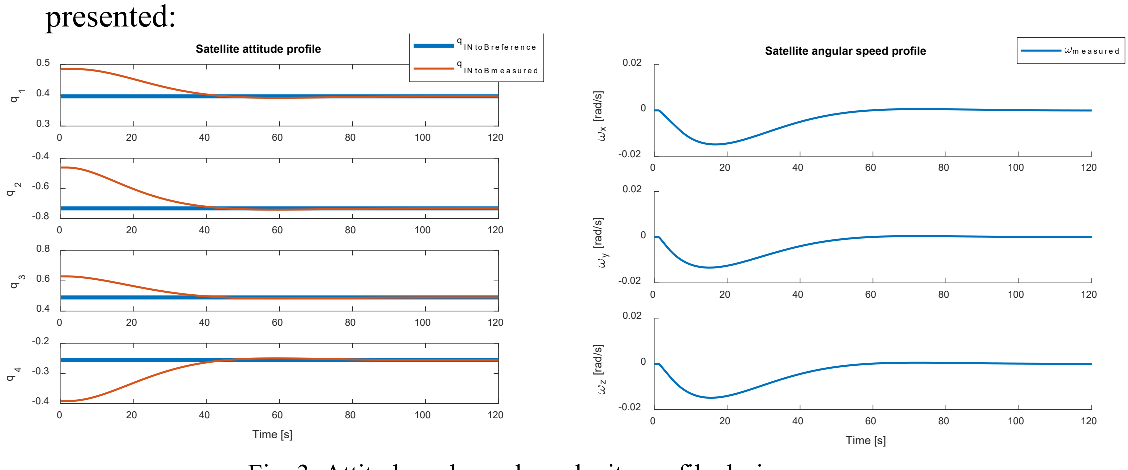

Fig. 3. Attitude and angular velocity profile during maneuver

By using the threshold profile designed in Fig. 2, the following variable FDI threshold profile presented in Fig. 4 is obtained during the nominal maneuver:

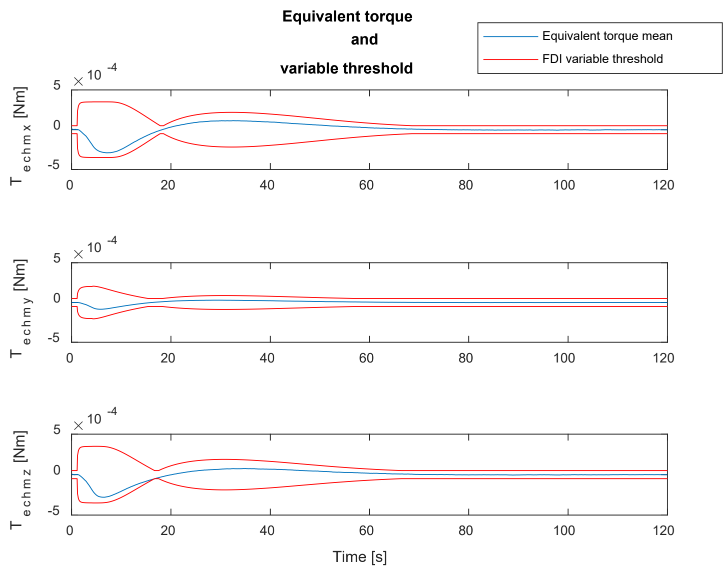

Fig. 4. Variable FDI threshold for equivalent torque

The variable FDI threshold profiles presented in Fig. 4 are derived using the parabolic equation (3), based on the control torque generated by the reaction wheels, as presented in Fig. 5.

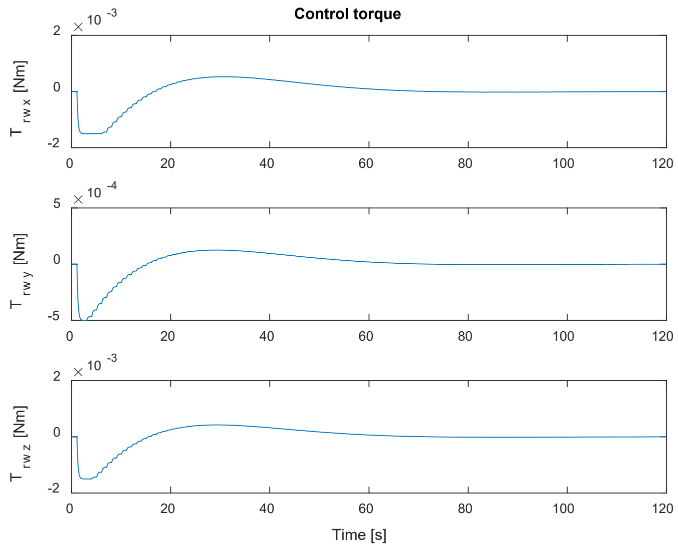

Fig. 5. Command torque generated by reaction wheels

As one can notice in Fig. 4, the variable FDI threshold is capable to bound the equivalent torque, $\boldsymbol{T}_{echm}$, in the presence of high dynamic uncertainties of 20%.

Furthermore, to observe the positive impact of using a variable threshold approach, one performed simulations considering various faults on the last part of the maneuver by using the fix and variable FDI thresholds, one at a time. The simulation fault is scheduled to appear at the second 75 of simulation for all cases. For the fixed threshold the p_{ech} superior value from Table 1 is chosen. The results of the comparison are presented in Table 2, where the detection time represents the time of the simulation when the fault is detected, and the isolation time is the time of simulation when the fault is isolated:

Table 2

Variable threshold performances

Fault	Fix threshold		Variable Threshold	
	Detection time [s]	Isolation time [s]	Detection time [s]	Isolation time [s]
Actuator axis x	193	197.8	98.2	103.1
Actuator axis y	598.9	603.8	170	174.6
Actuator axis z	250.9	255.8	108.4	113.3
Gyroscope axis x	579.2	582.4	75.2	80
Gyroscope axis y	869.6	873	454.7	457.2
Gyroscope axis z	616	619.5	196.5	199.3

The results presented in Table 2 show that the improvements in fault time detection are significant in the case of variable threshold strategy. The effects of the variable threshold are for sure visible for the cases when the satellite has a low angular velocity. In these cases, for a fault to become detectable, changes are needed in the system, so the effect of the fault should propagate in the system. The variable threshold reduces to minimum the propagation of fault in the system and can detect the fault faster due to the lower amplitude of the threshold.

5. Conclusions

In this paper is presented the detailed design of the FDI SMO system, being a hybrid FDI scheme based on a bank of sliding mode observers and Gyroscope Monitoring functionality. The main detection of the fault is provided by the Global SMO by using the equivalent torque, computed based on the equivalent injection signal. The isolation of the fault is performed based on the information provided by the Gyroscope Monitoring block and the isolation observers. The isolation observers are designed to take into consideration possible fault scenarios. In the hypothesis of high satellite dynamic uncertainties, a fixed FDI threshold will not provide satisfactory time detection performances, so a variable threshold is proposed and designed. The variable threshold is designed using a parabola profile bounded by superior and inferior thresholds, considering the worst-case dynamic uncertainties of 20%, Fig. 2. The variable threshold is computed based on the command torque and a variable threshold profile is presented in Fig. 4 by performing a sun acquisition maneuver. The variable threshold strategy is tested on 6 different types of faults of actuators and gyroscopes. The results of Table 2 show considerable improvements in detection time.

R E F E R E N C E S

[1]. *Florin-Adrian Stancu, Adrian-Mihail Stoica*, Satellite FDI system design using sliding mode observers, Incas Bulletin, **vol.14**, issue 1/2022, pp 197-207

[2]. *Florin-Adrian Stancu, Adrian-Mihail Stoica*, Actuator fault reconstruction using FDI system based on sliding mode observers, Incas Bulletin, **vol.14**, issue 4/2022, pp 157-165

[3]. HERA mission, accessed 23/01/2022: https://www.esa.int/Safety_Security/Hera

[4]. *Hannah R. Goldberg, Özgür Karatekin, Birgit Ritter, Alain Herique, Paolo Tortora, Claudiu Prioroc , Borja Garcia Gutierrez, Paolo Martino, Ian 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

[5]. *Sergey Drakunov, Vadim Utkin,* Sliding Mode Observers. Tutorial., Proceedings of the 34th Conference on Decision & Control, New Orleans, 1995

[6]. *Indira Nagesh,* Fault diagnosis for a satellite system using sliding mode observers, 2015

[7]. *Christopher Edwards, Sarah K. Spurgeon,* Sliding Mode Control Theory and Applications, Taylor & Francis Group, 1998

[8]. ***https://gomspace.com/shop/subsystems/attitude-orbit-control-systems/nanotorque-gsw-600.aspx, accessed February 2023