University Politehnica of Bucharest

Aerospace Engineering

Summary of the Ph.D. Thesis

Fault detection and isolation for spacecraft control system

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CONTENT

Abstract

The thesis abstract proposes a fault detection and isolation (FDI) system for the control system of a CubeSat satellite based on a mathematical model by means of sliding mode observers (SMO). The FDI SMO system is based on the evaluation of the equivalent injection signal to detect and isolate faults occurring in the system using a bank of SMO observers, which is specifically designed for different types of faults that may occur in the system. To avoid the chattering phenomenon, caused by the signum function, a continuous approximation based on the sigmoid function is proposed. The fault detection is performed by evaluating the equivalent torque (based on the equivalent injection signal) provided by the global SMO estimator. To predetermine the nature of the fault, the satellite's angular velocity is estimated by approximating its profile with the help of linear regression, obtaining the residual between the measured and the estimated angular velocity. This information is used by the state observer bank to perform the isolation function by evaluating the equivalent torque. In order to minimize false alarms, the FDI variable threshold concept is proposed, which considerably reduces the number of false alarms and significantly decreases the fault detection and isolation time. To increase the representativeness of the simulation, the HW configuration of the Juventas satellite control system is proposed. An optical gyroscope, to measure the angular velocities of the satellite, is proposed to be used due to the reduced measurement noise. The FDI SMO system is tested in a large Monte Carlo campaign under the assumption of the following scenarios: orientation of the solar panels to the Sun, SSTO phase and the desaturation process of the reaction wheels with the help of thrusters. The FDI SMO system developed in Simulink is translated into C programming language using the auto coding process. Finally, the code is implemented in a representative HW system and tested to evaluate the execution performance, using the ZC702 development board. The operating system used to run the code on the ZC702 development board is an embedded Linux type.

Keywords: fault detection and isolation, sliding mode observer, equivalent injection signal, CubeSat

1. INTRODUCTION

The FDI system based on the sliding mode observer is developed, designed and implemented to monitor the operation mode of the actuators and the data provided by the sensors within the control system. The theoretical developments regarding the FDI system are illustrated, analyzed and validated using the Juventas CubeSat satellite model. Thus, the main objective is the development of an innovative method of monitoring the control system regarding the detection and isolation of faults, a process carried out autonomously without the intervention of the control centre located on the ground. The studies in [17] show that due to its complexity, the AOCS/ADCS/GNC system is one of the systems most prone to the occurrence of faults, with a failure rate of approximately 32%. The FDI system is required when the control system operates autonomously without human operator intervention. The FDI SMO system is required when the control system operates autonomously without human operator intervention. The FDI SMO system is designed so that its performance allows the identification of faults in an effective way. For this purpose, four criteria can be identified that must be met by the FDI SMO system:

- Promptness: this aspect refers to the time required to detect the fault. The detection time is determined as the time from when the fault occurred until it was detected by the system;
- Sensitivity: the minimum threshold above which the system considers the occurrence of a fault;
- Robustness: the ability of the system to provide as few alarms as possible;
- Accuracy: correct identification of the fault.

Consequently, since the probability of a fault in the control system is considerable, the development of an FDI system represents an important research direction in the space industry. Following the literature review, regarding the FDI system, an FDI method based on a mathematical model is chosen and proposed, being one of the most feasible methods to be implemented because it is desired to reduce the mass of the satellite to a minimum. From the model category, the observer based on the sliding mode method is selected, due to its increased robustness to parametric uncertainties and external disturbances. These key performances are of interest because of the parametric uncertainties present in the satellite dynamics, but also the variation of inertia tensor during the mission due to fuel consumption. External disturbances can be approximated on the ground but cannot be precisely known, so the method should be robust to this class of unknowns. Furthermore, even though sliding mode theory has been available since the early 1960s, its use in the field of FDI systems is recent, the method being overlooked until the proposal to perform the detection based on the equivalent injection signal. The fault reconstruction based on the equivalent injection signal is considered an element of interest, being specific to sliding mode observers.

2. HERA MISSION AND THE SATELLITE CONFIGURATION

HERA is a planetary defence mission for testing the possibility of deflecting asteroids to avoid collision with Earth. Juventas is one of the CubeSats on board HERA, chosen to design, implement and analyze the performance of the FDI SMO system. To increase the representativeness of the simulations and to design the SMO FDI system, the configuration of the CubeSat satellite is proposed. The Juventas satellite has a size of 6U according to the CubeSat standard and a total mass of 12 kg.

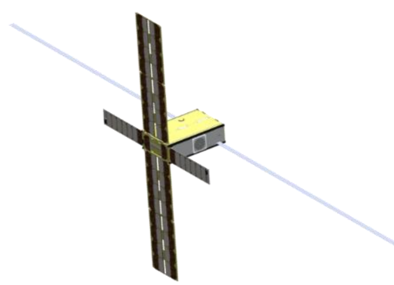

Fig. 2-1: Juventas satellite, [81]

The configuration of the control system is proposed, consisting of actuators and sensors, carefully established based on an analysis of the availability of the components on the market, but also the feasibility of their integration within the satellite. Finally, the following configuration is proposed:

- Optical gyroscopes VG1703;
- NanoTorque GSW-600 reaction wheels;
- NanoProp 6 DOF thrusters;

- NanoMind Z7000 on-board computer;

3. FAULT DETECTION AND ISOLATION BASED ON SLIDING MODE OBSERVER

To develop the FDI based on sliding mode observer, it is necessary to develop the dynamic and kinematic equation of the space vehicles under the assumption of a rigid body with 6 degrees of freedom. The reference systems used to represent the position and attitude of the Juventas satellite are defined, namely the J2000 Didymain ecliptic reference frame and the Juventas satellite reference system. The dynamics of the satellite are developed taking into account Juventas' configuration, in the presence of the gyroscopic effect generated by the reaction wheels. The effect generated by the control system is present in the dynamic equation through the torque generated by the reaction wheels or by the thrusters. The kinematic equation describes the attitude of the satellite. The attitude representation is based on quaternion parametrization to avoid Euler rotational singularities.

The attitude control system is based on a PD control law, constructed by using the attitude error and the angular velocity of the satellite. The PD command is executed using reaction wheels. Due to the reaction wheels saturation phenomenon (reaching the constructive maximum angular velocity of the reaction wheel), the desaturation process is proposed. The desaturation control law is based on reducing the angular momentum of the reaction wheels, to obtain the necessary torque of desaturation which reduces, due to the reaction of the control law PD, the angular velocities of the reaction wheels towards the reference value. The thrusters are in charge to execute the desaturation torque.

Based on the dynamic equation, the sliding mode observer is proposed to estimate the satellite's angular velocity using nonlinear dynamics, where the pseudo-sliding function is used to avoid the chattering phenomenon. The observer's objective is to minimize the error that represents the defined sliding surface itself. The stability of the sliding mode state estimator is evaluated using the η reachability condition in the presence of bounded disturbances and faults. The analysis result indicates that for a sufficiently large amplification term of injection signal, the η

reachability condition is satisfied, which implies that the sliding mode observer ensures convergence towards the sliding surface in a finite time interval. A particularity of the observer is represented by the possibility of reconstructing disturbances and actuator faults based on the equivalent injection signal. This is possible when the sliding surface is reached and maintained. At the same time, based on the reconstruction of the fault, developed under the name of the equivalent torque, the preliminary fault detection condition is proposed. Since the equivalent torque only contains information about the amplitude of the fault, it can be used for detection, but the nature of the fault remains unknown. To determine the nature of the fault(actuator or gyroscope defect) it is proposed to estimate the angular velocity of the satellite using linear regression on a reduced sample of previous angular velocity measurements. Thus, the angular velocity profile is approximated based on three linear functions that are updated at each moment, a procedure based on which the estimated angular velocity is obtained to finally obtain the residual. If the residual exceeds a predefined threshold, the possibility of a fault in the sensor is indicated. This information is used by the bank of observers to choose the group of observers (reaction wheel group, sensors group or thrusters group) from which the equivalent torque will be evaluated. The observer which provides the minimum equivalent torque is the one that isolates the fault.

The development of the FDI SMO system is based on the bank of observers which is composed of 10 sliding mode observers: a global observer with the role of detecting the fault and 9 observers designed considering the faults scenarios used to isolate the defect:

- Total failure of a reaction wheel;
- Total failure of a gyroscope;
- Stucked closed valve failure of a thruster.

The FDI SMO system architecture is defined by the following functionalities:

- Global observer – generates the equivalent injection signal;
- Fault detection – detects a fault, generates the variable FDI threshold and controls the bank of state observers;
- Gyroscope monitoring – checks isolation feasibility, checks if a gyroscope is frozen and provides information about the nature of the fault;

- Observers bank – contains the sliding mode observers and provides fault isolation information;
- Fault isolation – based on the information provided by the fault detection, gyroscope monitoring and the observers bank declares the fault and isolates it.

Using the Matlab simulator and the FDI SMO system, three basic scenarios are proposed for testing: the maneuver to ensure the solar panel orientation towards the Sun, the SSTO phase and the desaturation of the reaction wheels. The faults proposed to be detected and isolated are:

- Total failure of the reaction wheel, where it is no longer commanded and the information about the angular velocity of the wheel is not available.
- Thruster failure with fully closed valve;
- Total failure of the gyroscope;
- Frozen measurement of a gyroscope.

As previously described the sliding mode observer uses the pseudo-sliding function to reduce the chattering effect and obtain an interpretable injection signal with the objective to decide the presence of a fault. The pseudo-sliding function is configured such that the sliding mode observer exhibits increased robustness to parametric uncertainties of up to 20% and solar radiation pressure. Finally, the chosen configuration is proposed for the entire observers' bank. An element of novelty is represented by the proposal of a variable FDI threshold based on a parabolic profile, limited by an upper FDI threshold that represents the vertex of the parabola and a lower FDI threshold. The FDI threshold limits are decided by Monte Carlo simulations under the assumption of maximum disturbances and uncertainties.

The FDI SMO system is tested using the first scenario regarding the sun acquisition maneuver, using the Matlab/Simulink simulator, in a large Monte Carlo test campaign, where the parametric uncertainties are varied in a percentage of 20%, the disturbances are varied considering a position of the center of pressure that changes with respect to the center of mass between 0.01 – 0.1 m. Also, variations of the fault occurrence time between 5-120 seconds are tested. Finally, the variation of initial satellite states is considered where the initial attitude rotation is altered in the range of 2.5-20 degrees and a variation of angular velocity of 20% is tested. It is also observed that the detection of the fault is dependent on the amplitude and variation of the angular velocity.

The second scenario is represented by the SSTO phase, which assumes a stable orbit around the asteroid Didymain. It is worth noting that the SSTO phase involves the use of the FDI SMO system only in the detection configuration due to the low angular velocity of the satellite. The conclusion of the analysis is represented by the fact that the FDI SMO system is proposed as a precaution running during the SSTO phase to detect possible events that may endanger the safety of the Juventas satellite. The third scenario is represented by the desaturation process of the reaction wheels. Similarly, the desaturation process scenario presents a low angular velocity of the satellite, which implies the use of the FDI SMO system in the detection and isolation configuration for actuators only: reaction wheels and thrusters.

The cumulative Monte Carlo campaign results denote outstanding performance:

- 99.23% regarding correct detection;
- 94.27% regarding correct isolation;
- only one incorrect isolation.

To generate an implementation in the C language of the FDI SMO system, the SW V development cycle is proposed. The software implementation process is supervised by the following standards: ECSS-E-ST-40C, ECSS-Q-ST-80C and ECSS-E-HB-40A. Three development steps are proposed:

- model in the loop – the FDI SMO system is designed and tested in Simulink;
- software (SW) in the loop – the Simulink block containing the FDI SMO system is autogenerated and then tested in Simulink using the compiled version of the C code;
- processor in the loop – the source code obtained after the auto coding process is implemented on the target hardware (HW).

The FDI SMO Simulink model is developed following the autcoding rules. The auto generated code is integrated into the Matlab/Simulink simulator using the S-function block (which contains the auto generated code compiled and prepared to run in Simulink). For testing, the nominal case is considered, namely the sun acquisition maneuver in the presence of a fault on the x-axis reaction wheel. The results of the SW in the loop tests show identical detection and isolation time with the Simulink model, which confirms the correct functionality of the auto code. Next, the processor in the loop configuration is considered, where the NanoMind Z7000 onboard computer is selected, which is based on the Dual ARM Cortex A9 MpCore processor. Due to the high purchase cost, the alternative of a ZC702 development board containing similar HW is proposed. The operating system is based on a new trend in the space industry, called embedded Linux. The integrated auto code version for the processor in the loop testing is called the FDI SMO application, which is loaded together with the Linux operating system on the ZC702 development board by using an SD card. For testing purposes, the nominal case is considered, namely the sun acquisition maneuver in the presence of a fault on the x-axis reaction wheel. The results of the procesor in the loop tests show identical detection and isolation time with the Simulink model, which confirms the correct functionality. Finally, to evaluate the feasibility of implementing the FDI SMO application on the Dual ARM Cortex A9 MpCore processor, the size of the compiled application and the execution time are determined. From the memory point of view, the application does not impose integration issues. The peak time execution of the FDI SMO application is around 0.1159 ms. Considering these aspects is concluded that the FDI SMO application consumes negligible resources, thus demonstrating the feasibility of its integration on the on-board computer.

4. CONCLUSIONS

4.1. Publications

During the development of the sliding mode FDI system for the Juventas satellite, the following list of publications is presented:

1. Florin-Adrian Stancu, Adrian-Mihail Stoica: Satellites FDI system design using sliding mode observers, INCAS Bulletin, Vol.14, Issue 1, pp.197-207, https://doi.org/10.13111/2066-8201.2022.14.1.16, 2022
2. Florin-Adrian Stancu, Adrian-Mihail Stoica: Actuator fault reconstruction using FDI system based on sliding mode observers, INCAS Bulletin, Vol.14, Issue 4, pp.157-165, https://doi.org/10.13111/2066-8201.2022.14.4.13, 2022

3. Florin-Adrian Stancu, Victor Manuel Moreno Villa, Carlos Dominguez Sanchez, Andrei Valentin Plămădeală, Daniel Ovejero Provencio: Visual based GNC system from prototype to flight software, INCAS Bulletin, Vol.15, Issue 1, pp 97-106, https://doi.org/10.13111/2066-8201.2023.15.1.9, 2023
4. Florin-Adrian Stancu, Adrian-Mihail Stoica: Variable fault detection and isolation threshold based on sliding mode observers, sent to publication to UPB Scientific Bulletin
5. P. Bajanaru, R. Domingo Torrijos, D. Gonzalez-Arjona, F. A. Stancu, C. Onofrei, M. Marugan Borelli, R. Chamoso Rojo, C.G. Mihalache: Reconfigurable Co-Processor for Spacecraft Autonomous Navigation, OBDP2021- 2nd European Workshop on On-Board Data Processing (OBDP2021), 14-17 June 2021, Session 8, DOI: 10.5281/zenodo.5517286
6. D. Gogu, F. Stancu, A. Pastor Gonzalez, D. Fortun Sanchez, D. Gonzalez-Arjona, O. Muller, M. Barbelian, V. Pana: Boosting Autonomous Navigation Solution based on Deep Learning using new rad-tol Kintex Ultrascale FPGA, OBDP2021- 2nd European Workshop on On-Board Data Processing (OBDP2021), 14-17 June 2021, Session 3, DOI: 10.5281/zenodo.5520545
7. F. A. Stancu, J. R. Garcia, A. Pellacani, D. Gonzalez Arjona: Validation process from models to HW avionics in the frame of HERA autonomous navigation, DASIA (Data system in aerospace) 2021, eurospace.org/wp-content/uploads/2021/06/dasia-2021-programme-19-09-2021-21h45-final.pdf

4.2. General conclusion

A fault detection and isolation system is proposed, designed and implemented for a CubeSat satellite, called Juventas. The FDI system is developed for the Juventas control systems using sliding mode observers, which falls in the model-based FDI approach. The design of the sliding mode observers is based on the nonlinear dynamics of the satellite, taking advantage of the high robustness to parametric uncertainties and disturbances. To avoid the chattering effect is proposed a linearization of the signum function, called pseudo-sliding function used to obtain a smoothed equivalent injection signal. An important particularity of the sliding mode observer is the possibility to reconstruct disturbances and actuator faults based on the equivalent injection signal. The FDI SMO is based on a global observer and a bank of sliding mode observers designed considering different fault scenarios. The global observer is only used to detect a possible fault by evaluating the equivalent torque (based on the equivalent injection signal) and the isolation is performed by evaluating the observer's equivalent torque from the observers' bank. In order to detect if is a sensor or actuator torque fault, a preliminary check is performed by estimating the angular velocity of the satellite based on the previous measurements using a linear regression approximation. The FDI SMO can detect and isolate faults like:

- Reaction wheel malfunction;
- Gyroscope malfunction;
- Gyroscope frozen measurements;
- Thruster malfunction – completely closed.

The pseudo-sliding function is configurated to ensure robustness in the case of a high percentage of parametric uncertainties and solar pressure disturbance.

For testing purposes, a Simulink simulator is built where the main functionalities are considered: control system, actuator models, solar radiation pressure, malfunction simulations and FDI SMO system. The FDI SMO is tested using a large Monte Carlo campaign with the following scenarios: sun acquisition phase, SSTO orbit recursive attitude command and reaction wheels desaturation using thrusters. During the test campaigns, the key FDI system was subjected to different testing conditions, like: up to 20% parametric uncertainties, different solar pressure disturbances, time of the malfunction appearance, different initial satellite attitude and angular velocity and different malfunction cases. The results show a high rate of fault detection (around 99%) and isolation (around 94%). During the entire testing campaign, only one incorrect isolation was noticed.

The FDI system is implemented in C language by using autocoding techniques using the embedded coder toolbox of Matlab/Simulink. The auto generated code is first tested in code in the loop architecture (in Simulink, using S-function) where the SW showed similar behavior with the Simulink FDI model. Finally, the auto generated code is implemented on the target HW, ZC702 development board. The FDI SMO application is created and run using a dedicated operating system based on Linux specifically developed embedded systems. The FDI SMO application is running in a maximum of 0.1159 ms (per call), which proves the feasibility of implementation using the Dual ARM Cortex A9 Mp Core processor.

4.3. Personal Contributions

The following list highlights a selection of the most important personal contributions:

- Proposal to solve the fault detection and isolation problem using sliding mode observers;
- Definition of the satellite configuration;
- Proposal to use VG1730 optical gyroscope to measure the angular velocity of the satellite;
- Design of the attitude control and desaturation system for the Juventas satellite;
- Proposal to use the pseudo-sliding function to directly obtain the smoothed equivalent injection signal to perform the fault detection;
- Detection of the fault using the global observer, evaluating the equivalent torque determined based on the equivalent injection signal;
- The design of the preliminary detection of faults present in the angular velocity measuring units by estimating the angular velocity using the approximation with a linear regression based on the least squares method;
- Design the bank of the sliding mode observers' bank;
- Design of sliding mode observer considering the nonlinear dynamics of the Juventas satellite;
- Design a hybrid FDI SMO architecture that is robust to external disturbances and parametric uncertainties;
- Introduce the concept of variable threshold design with the help of the parabolic equation;
- Development of the Matlab/Simulink simulator to test the system and increase the representativeness of the simulations;
- Configure the pseudo-sliding function for the global estimator and observers' bank;
- Configure the variable FDI threshold based on parametric uncertainties and bounded disturbances;

- Perform a large Monte Carlo test campaign;
- Implementation, validation and verification of the FDI SMO system following the ECSS-E-ST-60-30C standard;
- SW implementation of the FDI SMO system based on the concept called “SW V cycle”;
- Verification and validation of FDI SMO application in software in the loop and processor in the loop;
- Implementation, validation and verification of FDI SMO application following ECSS-Q-ST-80C, ECSS-E-ST-40C and ECSS-E-HB-40A standards;
- Demonstrate the feasibility of implementing the FDI SMO application using a Dual ARM Cortex A9 MpCore processor.

4.4. Future work

The following future work is proposed:

- Extending the bank of observers considering additional failure scenarios: loss of control torque generation efficiency in reaction wheels and loss of sensor measurement sensitivity;
- Use a number of four reaction wheels in a pyramidal configuration in such a way as to allow the reconfiguration of the control system in case of malfunction;
- Simulink FDI SMO model optimization to further reduce the time execution of the application using a Dual ARM cortex A9 processor.

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