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Korichi Kouider and Khedaiche Redouane

Advanced satellite attitude fault diagnosis in low orbit

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ملخص

تتناول هذه الرسالة مشكلة التشخيص التلقائيلأعطال مستشعر الجيروسكوب الذي يقوم بقياس السرعة الزاوية للساتل. الهدف الرئيسي من هذه الأطروحة هو الكشف الآلي لأعطال الجيروسكوب بواسطة مؤشر الصحة، هذا المؤشر يملك الآلية التي يستطيع من خلالها الكشف عن أي خطأ يمكن أن يتعرض له الجيروسكوب. بعد الكشف الصحيح للخطأ يجب تحديد موقع هذا الخطأ والذي سيكون من خلال بناء مساحة ميزة تكون قادرة على التمييز بين ظروف التشغيل العادية و ظروف التشغيل الفاشلة ، ليسهل بعد ذلك تحديد حجم هذا الخطأ ثم إنشاء قانون تحكم جديد يتكيف مع هذا الخطأ.

الكلمات الدالة:الكشف التلقائي، التوطين، الجيروسكوب، السرعة الزاوية، مؤشر الصحة، مساحة ميزة، الساتل.

Abstract:

This thesis addresses the problem of automatic fault diagnosis of the gyroscope sensor - which measures the angular velocity of the satellite. The main goal of this thesis is the automatic detection of gyroscope faults by means of the health indicator; this indicator has a mechanism by which it can detect any fault that the gyroscope may be exposed to. A feature space is buildingto be able to distinguish between normal operating conditions and failed operating conditions, after the correct detection of the fault, direction indicator is used for fault localization, the component responsible of the fault must be determined, to facilitate then determine the amplitude of this fault and then create a new control law that adapts to this fault (FTC).

Keywords: Satellite, Automatic detection, Localization, Gyroscope, Angular velocity, The health indicator, Feature space.

Résumé:

Le travail présenté dans ce manuscrit traite la problématiquede diagnostic automatique des défautscapteurgéroscop qui calcule la velocitéangulaire du satellite. L'objectifprincipale de ce travail de projet de fin d'étudeest de mettreen place un alghorithmecapable de détecter et localiser les défautssceptible de survenir sur le géroscop par le baie d'un indicateurrévelant son état de santé, cetindicateurdéspose d'un mécanismeluipermmetant de détecterl'ocurance de tout sort de défauts qui pourraitimpacter le géroscop, ensuite un indicateur de direction estutilisé pour localiser le défaut.Afin de réalisercetobjectif un espace de representation estconstruit pour maximiser la discrimination entre un fonctionnement normal et un fonctionnementdéfaillant, et isolél'élementrésponsable de défaut, cela permet d'estimerensuitel'amplitude de défautafin de reoconfigurer la commande.

Mots clés: Satellite, DétectionAutomatique, localization de défaut, Gyroscop, Indicteur de degradation, Espace de representation.

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KorichiKouider

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KhedaicheRedoune

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Acronyms

FTC	FaultTolerant Control
FDD	FaultDetection and Diagnosis
FDI	FaultDetection and Isolation
ADCS	Attitude Determination and Control System
GSE	Gyro-Stellar Estimator
SST	Satellite Star Tracker
MSV	Survival Mode
NMO	Normal Mode of Operations
PI	Proportional-Derivative control law
ECI or FI	Earth Centered Inertial
ECEF or FE	Earth Centered Earth Fixed
FO	Orbit Frame
FB	Body Frame

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1.1. General context

This thesis discusses the design of an Active Fault Tolerant Control (FTC) strategy for theimprovement of Attitude Determination and Control System (ADCS).

When we talk about a Fault-tolerant system (FTC) we are talking about a smart system that can maintain desired goals with faults, and this is its strongest point Especially in the space field that needs autonomy in control because the satellite in its LEO orbital position can't be tracked continuously by the control center. Furthermore, FTC can ensure system stability and maintaining acceptable performance. Before going further into FTC, however, it is necessary to address the faults detection and diagnosis (FDD).

In general, there are two main diagnostic methods: model-based diagnostic and data-based diagnostic. The first method has several challenges, like finding the mathematical model that fits the most the dynamic behavior of that system - if the system is physical, we use physical rules, and if it is chemical we use chemical rules, and so on-. This topic - modelization - is a specialty of a group of scientists and researchers, while the second method depends on historical data collected during the operational phase of some given space mission or simulation data (which is the method used in this thesis).

What we discussed about how FTC works and its relationship to FDD will be clear by describing the architecture of the active FTC as shown in the following figure:

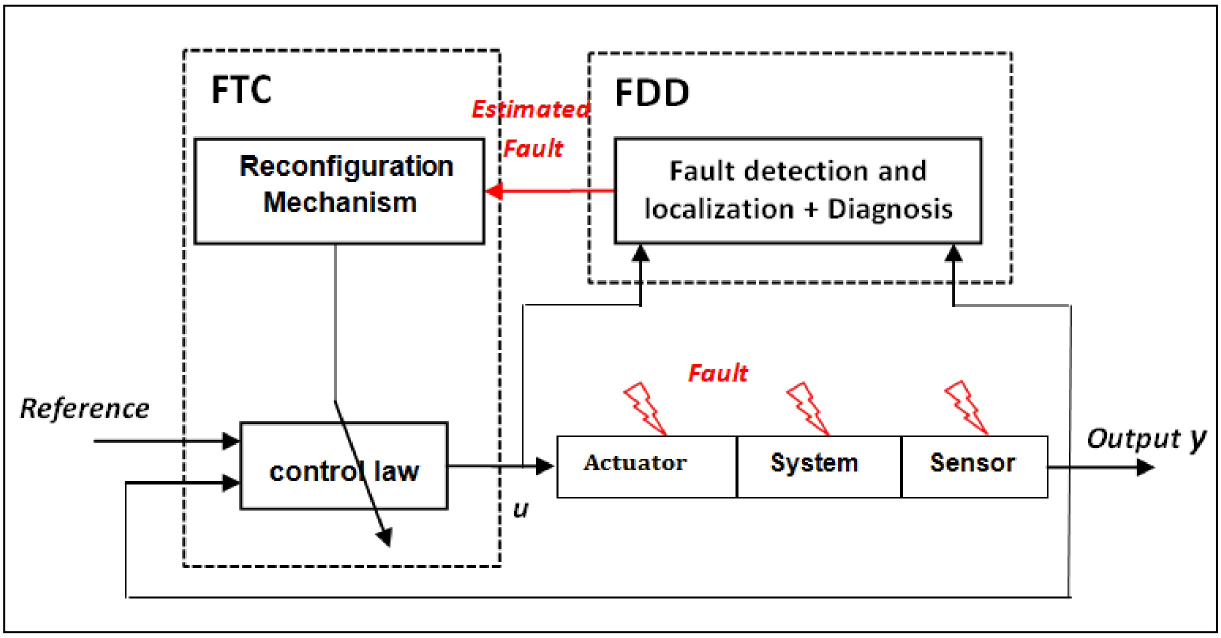

Figure 1.1: Schematic diagram of an active FTC control law [1]

The FTC system is based on the dual operation of the FDD and FTC blocks, which can be summarized as follows:

FDD Block: This block performs three consecutive functions, which are the detection of faults, their localization, and magnitude. so once a fault appears, this block provides this three information - its occurrence, location, and magnitude - to the FTC block and this is done automatically.

FTC Block: This block is activated after it is provided with information about the occurrence of a fault by the FDD block. Based on this information and the fault that originated, the FTC block creates a new control law that adapts to this fault and this is done automatically as well

In what follows we will provide some information in the field of satellites in the form of a question and answer, then we provide information about the ALSAT-2 satellite that we are studying.

1.1.1. What Is a Satellite?

A satellite is an object that moves around a larger object. Earth is a satellite because it moves around the sun. The moon is a satellite because it moves around Earth. Earth and the moon are called "natural" satellites.

But usually when someone says "satellite," they are talking about a "man-made" satellite. These machines are launched into space and orbit Earth or another body in space.

There are thousands of man-made satellites. Some take pictures of our planet. Some take pictures of other planets, the sun, and other objects. These pictures help scientists learn about Earth, the solar system, and the universe. Other satellites send TV and phone signals around the world. Scientific satellites, on the other hand, perform predetermined scientific experiences designed to run in the space environment. [18]

1.1.2. Why Are Satellites Important?

Satellites fly high in the sky, so they can see large areas of Earth at one time. Satellites also have a clear view of space. That's because they fly above Earth's clouds and air.Before satellites, TV signals didn't go very far. TV signals only travel in straight lines. So they would go off into space instead of following Earth's curve. Sometimes they would be blocked by mountains or tall buildings.

Phone calls to faraway places were also a problem. It costs a lot and it is hard to set up telephone wires over long distances or underwater.

With satellites, TV signals and phone calls can be sent up to a satellite. The satellite can then send them back down to different spots on Earth. [18]

1.1.3. What Are the Parts of a Satellite?

Satellites come in many shapes and sizes. But most have at least two parts in common - an antenna and a power source. The antenna is used to send and receive information. The power isone or several solar panelsand battery. Solar panels make power by turning sunlight into electricity.

Many satellites carry cameras and scientific sensors. They may gather information about Earth's land, air, and water. Or they may collect data from the solar system and the universe. [18]

1.1.5.ALSAT-2 space program

1.1.5.1.Alsat-2

Alsat-2 is a constellation of two Algerian Earth observation micro-satellites launched in 2010 and 2016 respectively. The two satellites managed by the Algerian Space Agency provide panchromatic images with a resolution of 2.5 meters and multispectral images with a resolution of 10 meters. High-quality data to use in a variety of applications: mapping, agricultural, forestry, water, mineral and oil resource management, crop protection, natural disaster management, and land planning.

1.1.5.2.History

In early 2006, the Algerian Space Agency signed, as part of its Alsat program, a contract with EADS Astrium for the acquisition of two micro Earth observation satellites [1]. The first Alsat-2Asatellite is developed and tested in France, at EADS Astrium premises while the second (Alsat-2B) is integrated and tested by Algerian engineers at the satellite development center (CDS) in Oran.The Alsat-2B was launched on September 26, 2016 by a PSLV-C35 [16] [17]

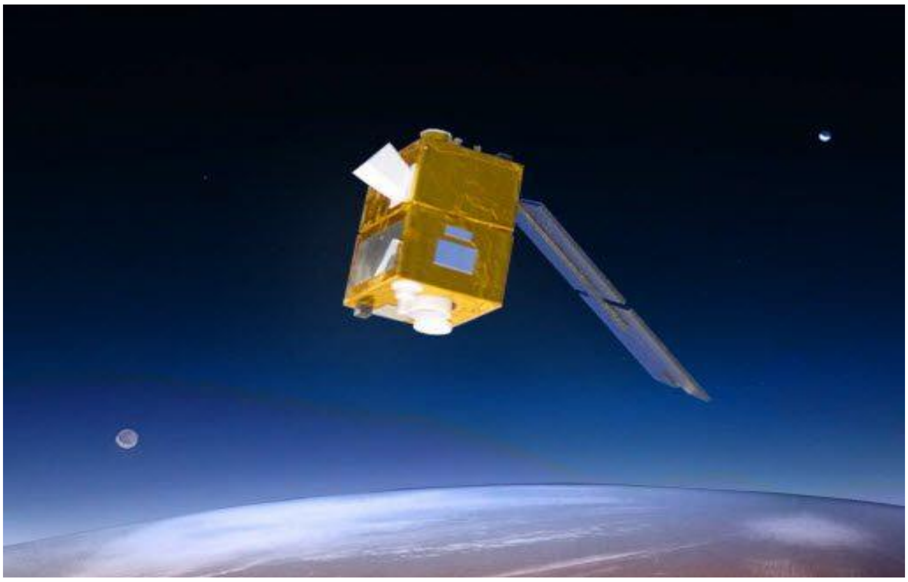

Figure 1.2: AlSat-2 satellite [16] [17]

AlSat-2B – (Algeria Satellite 2B)

It is the second satellite launched by Algeria within its AlSat-2 space program in the Visual Earth Observation Project of the Algerian National Center for Space Technology, (CNTS). This satellite is intended to take pictures from the Earth and send them to the space science station in Algeria to be used in building roads, dams and airports. It is a large project launched by the government Algerian as a program to develop space research and send a constellation of satellites, specifically designed for scientific research, weather monitoring, earthquake monitoring and natural disasters. See [16]

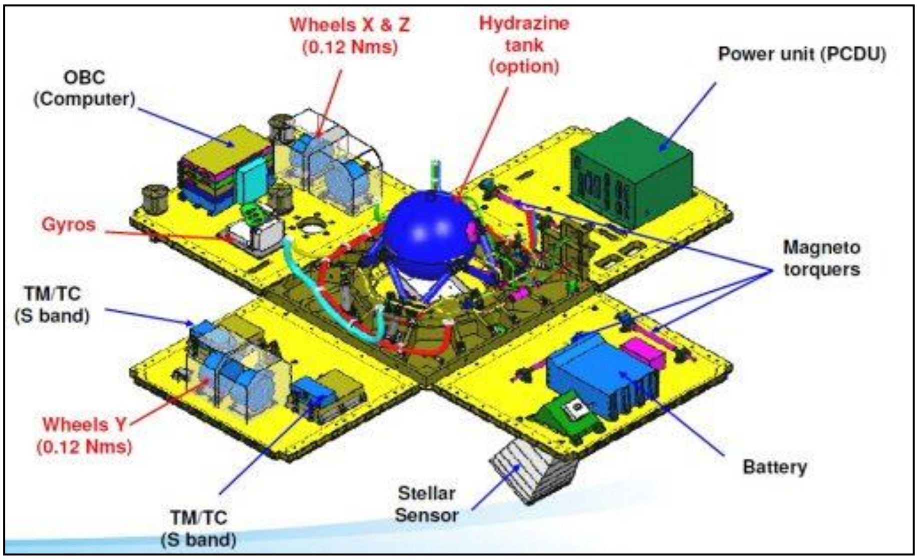

Figure1.3 : Internal components of AlSat-2B [16] [17]

AlSat-2B is based on the AstroBus-100 satellite platform that is part of a family of satellite buses covering a Low Earth Orbit mission range from 125 to 4,000 Kilograms. The AstroBus satellites are built to share a number of common avionics components to streamline the production line and reduce overall cost. The small AstroBus-100 is the extension of the AstroBus line to the lowest size range with evolutions through Airbus developments as well as the Myriade platform originally developed by the French Space Agency CNES for very lightweight satellite missions [16].

The 116-Kilogram AlSat-2B satellite is 0.6 by 0.6 by 1.0 meters in size and makes use of a box-shaped bus structure using external panels made of composite panels that host the various internal and external satellite subsystem components. The nadir panel of the satellite hosts the propellant tank and launch vehicle interface while the zenith panels build the interface with the NAOMI imaging payload.See [16] [17].

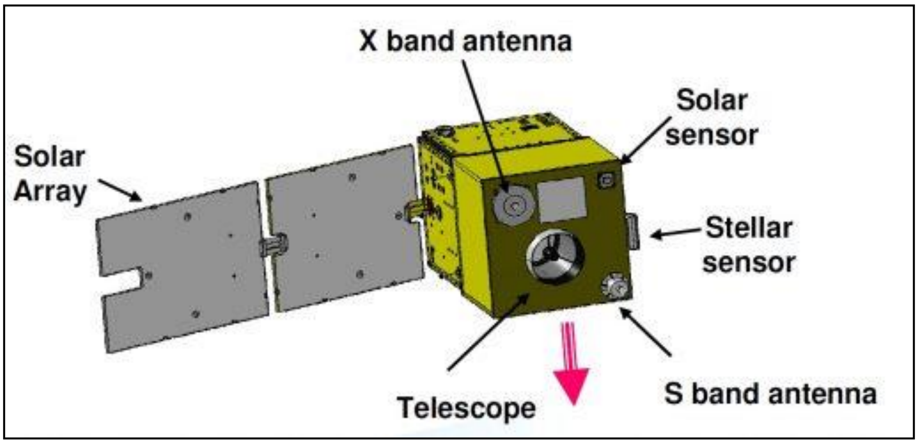

Figure 1.4: Illustration of the AlSAT-2b [16] [17]

The satellite hosts a single two-panel solar array featuring Gallium-Arsenide Solar Cells to deliver an end-of-life power of 180 Watts, fed to a 15 Amp-hour battery. The three-axis stabilization of the spacecraft is accomplished with a number of attitude sensors and actuators. Attitude Determination is provided by a Star Tracker that captures images of the space-facing side to use bright stars as reference for the precise calculation of the satellite's three-axis orientation in space. A three-axis magnetometer gathers data on the magnetic field to provide the information needed for the actuation of the magnetic torque rods. Body rates are measured by an Inertial Measurement Unit for use in the initial de-tumble and during maneuvers. Three sun sensors come into play in satellite safe mode to keep the solar panel pointed to the solar vector for power generation.

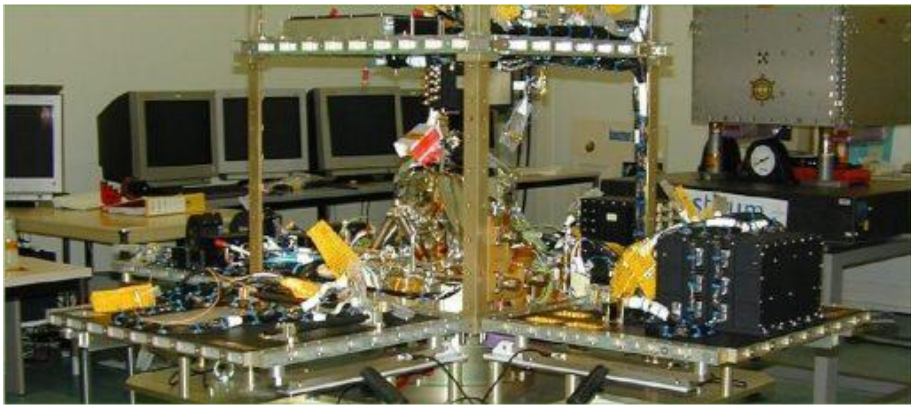

Figure1.5: AlSat-2B development [17]

Attitude Actuation is provided by four 0.12Nms reaction wheels installed in two reaction wheel assemblies. Three magnetic torquers are required for reaction wheel momentum dumps and during satellite safe mode. Attitude control on the spacecraft is sufficiently precise for pointing the satellite to the correct sector on the ground that is to be imaged.

1.2. Proposed approach

In this section, we will highlight the suggested approach, through which we can perform sensor fault detection and diagnosis and we can also make certain decisions in the event of a fault. In this thesis, we will rely on a database in the targeted diagnostic process for the gyroscope sensor that is important in the ADCS loop.

Most methods of discovering faults depend on the comparison between the observed values with the estimated behavior most reliable one with another sensor with higher precision. Therefore in this thesis, we will use SST measurements with gyroscopes measurements to make comparisons and generate residues. See figure 1.6

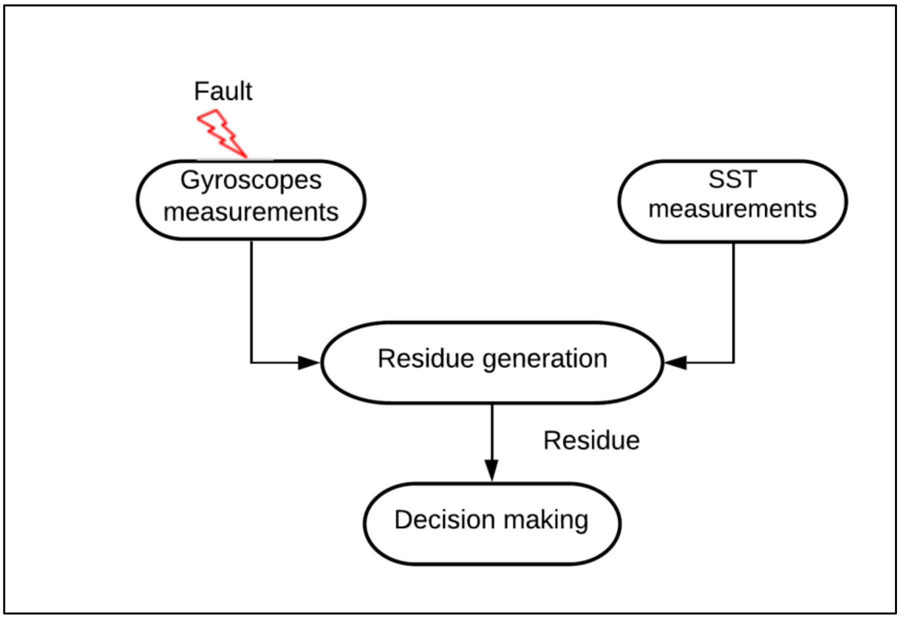

Figure I.6: Databased diagnosis.

If we want a fault detection and diagnosis using historical data, it is necessary to study a specific signal called a fault indicator or residue, and this residue is the one who determines the new command in case of a fault.

We notice from the previous figure that this is done through two stages of residue generation and residue analysis and assessment by a decision system. The role of the decision system is to determine whether the residue amplitude requires alarm raising or not, to avoid the so-called false alarms.

1.2.1.Residue generation

As we have said, the generation of residues is the result of a comparison of the measurements of process signals, actuators or sensors, with the estimated values provided by the model, these residue equals zero or its affinity in normal operating conditions and differs from zero inthe presence of a fault. Quality generating residues are essential to ensure theperformance of an intelligent diagnostic system. For more information On residue generation methods, see [1].

1.2.2. Decision making

This stage comes after the residue generation stage, which is the stage of the residue analysis in order to decide whether there is a fault or not and may include isolation of the element failing. Detection quality depends on two parameters, false alarm and non-detection. It is good for our system to be in between. A threshold is used to avoid false alarm. Ways to avoid false alarm can be found at [1]

1.3. Organization

The organization of this thesis is structured in the following manner :

Chapter2: Satellite fault-tolerant control. In the beginning of the chapter we present an overview of Attitude Control and what it needs from general concepts and mathematical equations, after this we provide an explanation of the main diagnostic steps and what we need in our work in the field of diagnosis, so we move on to explain the Classification of FTC approach and describe the architecture of an active FTC controller, Let's finally end with Objective of this work**.**

Chapter 3:Proposed approach for fault tolerant control of ADCS. In the third chapter, which is the most important chapter in this thesis, because we will explain through it the motivations and challenges facing the attitude control system and the importance of its accuracy in early detection of faults, and its diagnosis, as we will explain at first the proposed approach in detail then we present the model used and the results obtained secondly to finally finish with a general conclusion about the separation.

Chapter 4: General conclusion and perspective. This chapter summarizes the contributions of this dissertation, and discusses the possibility of improving and developing the future Attitude Determination and Control System.

Chapitre II : Satellite tolerantfault control

2.Satellitetolerantfault control

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2.1. Introduction

In this chapter, before we talk about FTC - which we will reach in our work - the goal of our work must be explained by attitude control loop and a mathematical model that describes the movement of a satellite around its center of mass- which defines the main benchmarks used in attitude Modeling as well mathematical tools for representing the attitude of a satellite, the global equation system which combines the dynamic and kinematic equations of the motion of a satellite - first, to explain secondly the satellite fault diagnosis, let's finally finish By studying Bibliographic on the fault-tolerant order of satellites and the goal of our work.

2.2.Attitude Control

The orientation of the satellite and its mathematical model can be derived in different frames. That's why it's good to start with some definitions and laws that explain the attitude of the satellite.

2.2.1. ADCS Attitude Determination and Control System

The ADCS of satellites (microsatellites in particular) - like the famous Myriade family - provides three-axis stabilization for the different types of pointing (nadir, inertial, etc.). Control is provided by the reaction wheels.

A general representation of an attitude control system is illustrated in the following figure:

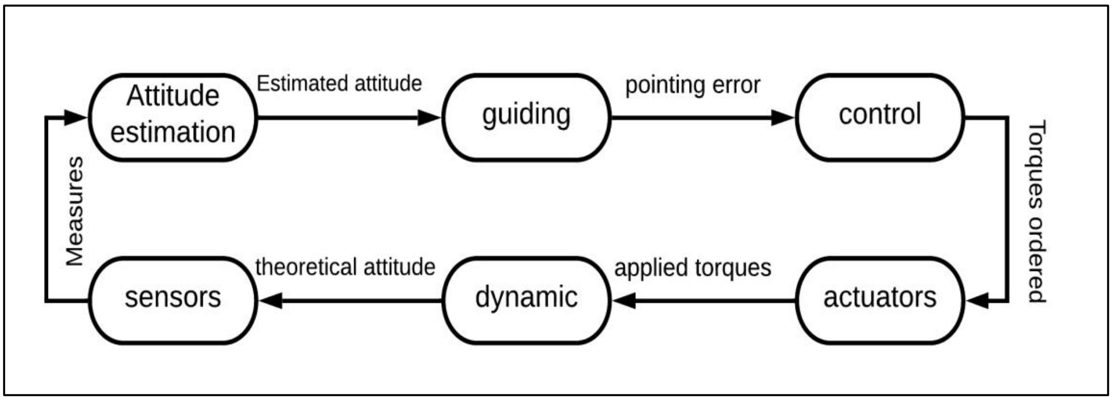

Figure 2.1. A general attitude control architecture

We can explain the different parts of the system in Figure 2.1 as follows:

1- Sensors: the satellite’s components that provide attitude measurements. See satellite sensors in detail[2] [3]

2-Attitude estimation (where am I): the estimation is made from the attitude measurements delivered by the sensors. Said measurements are naturally subject to noise, in which case an estimate (Kalman or other) is necessary.

3-Guidance (where I want to go): from guidance instructions sent by the control center to point the satellite towards a given area in space (astronomy) or on the surface of the earth (imagery or radar).

4- Control (how to go there): from the pointing errors obtained by the guidance, the control calculates and generates the torque commands necessary to respect the specification limits (ex: <0.1 °)

5- Actuators: technological mechanisms installed on board to execute the torques requested by the control (ex: reaction wheels). See satellite actuators in detail [2] [3]

6- Dynamics: for simulation, this is the mathematical model defining the relationship between the torques exerted on the satellite and the kinetics. And for real satellites, the dynamics represent the natural behavior of attitude in response to the applied torques.

2.2.2. Satellite attitude modeling

2.2.2.1.Angular Velocity

Angular velocity, ω is defined as the rate at which a rotation matrix changes. It is used to study the angular displacements that occur over time. Angular velocities are dependent on the reference frames and ω indicates the angular velocity of Fa relative to Fb

2.2.2.2.Attitude Representation

The attitude of a satellite is its angular orientation in space. It is defined as a relationship between two coordinate systems i.e. the orientation of the satellite reference expressed in a given reference, generally inertial or local orbital[1]. The overall movement of a satellite is characterized by its position, velocity, attitude, and angular velocity. The first two quantities describe the rotational movement of the center of mass of the satellite around the earth, so they are part of the theory of orbit determination. The last two quantities describe the rotational movement of the satellite body around its center of mass, and they are the subject of this thesis on determining the attitude of the satellite, in particular how it is estimated and how to determine its variation. The purpose of this section is to describe each attitude representation method, as well as the main relationships for their integrations and their interconversion. The derivations and detailed discussions on Attitude parameterization methods are available in references [3] [5].

([1]): For reference frames see: [3] [4]. Forframestransformationsee: [2]

2.2.2.2.1.Euler Angles

Euler angles are commonly used to describe the rotational movement of a rigid body such as planes, boats, submarine vehicles, and satellites. In this attitude description method, the rotation of the satellite around its center of mass is considered as a succession of three elementary rotations; since the order of these rotations can be reversed there are 12 possible rotation sequences that are also divided into two groups six symmetrical and six antisymmetrical.

2.2.2.2.2. Unit Quaternions

The quaternion is a second alternative to the angles of Euler which makes it possible to get rid of the singular angular configurations. According to Euler's theorem, a rotation of a rigid body in space can be expressed as a rotation by an angle (Φ) around an instantaneous axis of rotation (e)[3].[4]

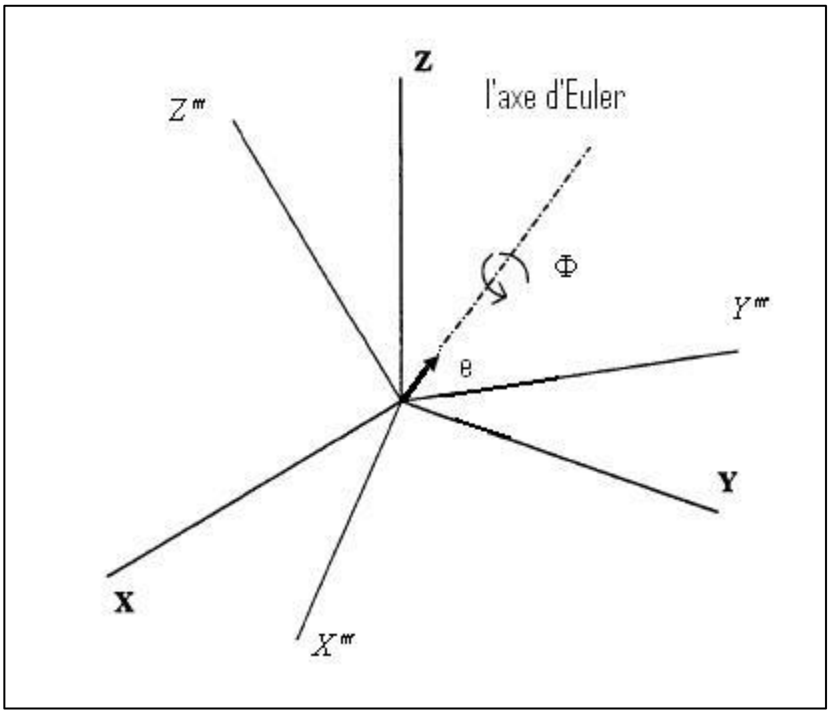

Figure 2.2: Geometric representation of a quaternion [4]

The unitary quaternion is composed of a unitary vector e, called the Euler axis, and an angle of rotation Φaround this axis. It is defined by :

$\mathbf{q} = [\, q_1 \quad q_2 \quad q_3 \quad q_4]^T$

Such as

$q_1 \equiv e_x \sin\left(\frac{\Phi}{2}\right)$

$q_2 \equiv e_y \sin\left(\frac{\Phi}{2}\right)$

$q_3 \equiv e_z \sin\left(\frac{\Phi}{2}\right)$

$q_4 \equiv \cos\left(\frac{\Phi}{2}\right)$

q_1, q_2, q_3: Are the imaginary parts of the quaternion;

q_4: is called the real part of the quaternion;

Φ : The angle of rotation around the Euler vector;

$\mathbf{e} = [e_x e_y e_z]^T$= Euler vector (unitary);

The components of a unitary quaternion satisfy the following property:

$q_1^2+q_2^2+q_3^2+q_4^2 = 1$

Therefore, the rotation matrix **A** in terms of a quaternion can be obtained by theangle rotation Φ around the axis**e**. Details on how to get this matrix ofrotation are given in [4].We limit ourselves to giving its expression according to the quaternion of orientation.

$$A = \begin{bmatrix} q_1^2 - q_2^2 - q_3^2 + q_4^2 & 2(q_1q_2 + q_3q_4) & 2(q_1q_3 + q_2q_4) \\ 2(q_1q_2 - q_3q_4) & -q_1^2 + q_2^2 - q_3^2 + q_4^2 & 2(q_2q_3 + q_1q_4) \\ 2(q_1q_3 + q_2q_4) & 2(q_2q_3 - q_1q_4) & -q_1^2 - q_2^2 + q_3^2 + q_4^2 \end{bmatrix}$$

2.2.2.3.Conversion between Euler Angles, Quaternion

In this section we can explain only two transformations (from Euler Angles to Quaternion and vice versa) which are used in the Simulink model, see [4] :

2.2.2.3.1. Conversion of Euler angles to quaternion

The quaternion associated with the sequence 2-1-3i.e. ($\theta \rightarrow \phi \rightarrow \psi$)) is given by

$$\mathbf{q} = q_\theta q_\phi q_\psi = \left(\cos\frac{\theta}{2} + \sin\frac{\theta}{2}\right)\left(\cos\frac{\varphi}{2} + \sin\frac{\varphi}{2}\right)\left(\cos\frac{\Psi}{2} + \sin\frac{\Psi}{2}\right) \quad (2.1)$$

After calculation, we find

$$q_1=\sin\frac{\varphi}{2}\cos\frac{\theta}{2}\cos\frac{\psi}{2}+\cos\frac{\varphi}{2}\sin\frac{\theta}{2}\sin\frac{\psi}{2}$$

$$q_2=\cos\frac{\varphi}{2}\sin\frac{\theta}{2}\cos\frac{\psi}{2}+\sin\frac{\varphi}{2}\cos\frac{\theta}{2}\sin\frac{\psi}{2}\quad(2.2)$$

$$q_3=\cos\frac{\varphi}{2}\cos\frac{\theta}{2}\sin\frac{\psi}{2}+\sin\frac{\varphi}{2}\sin\frac{\theta}{2}\cos\frac{\psi}{2}$$

$$q_4=\cos\frac{\varphi}{2}\cos\frac{\theta}{2}\cos\frac{\psi}{2}+\sin\frac{\varphi}{2}\sin\frac{\theta}{2}\sin\frac{\psi}{2}$$

2.2.2.3.2. Conversion ofquaternion to Euler angles

$$\theta = \arctan\left(\frac{2\,(q_1q_3+q_2q_4\,)}{-q_1^2-q_2^2+q_3^2q_4^2}\right)$$

$$\varphi = \arcsin\left(-2\,(q_1q_3+q_1q_4)\,\right) \qquad (2.3)$$

$$\psi = \arctan\left(\frac{2\,(q_1q_2+q_3q_4\,)}{-q_1^2-q_2^2+q_3^2q_4^2}\right)$$

2.2.2.4.Satellite equations of motion

This section presents the system of equations governing the attitude of a satellite. The movement of a rigid body in space can be broken down into two elementary movements: a translational movement of the center of mass, and a rotational movement around an axis passing through the center of mass of the body. Generally, attitude control theory considers only the second effect and ignores the first, because it is part of the orbital motion [3].

The equations that govern the attitude of a satellite can be classified into two parts:

-The dynamic equations are interested in the relationship that exists between the external forces acting on the satellite, and its angular velocities as a function of time in an inertial frame.

-The kinematic equations define the relationship between the change in the orientation of the satellite and its angular velocities independently of the forces acting on it.

2.2.2.4.1.Dynamic equation of the satellite

The attitude can be described precisely by the orientation of the local frame of reference "Fb" (integrated into the satellite (body frame)) relative to an inertial frame of reference "Fi" :

The dynamics of the satellite attitude are governed by the following Euler's equation[6]::

$$\dot{\vec{h}}_c = \vec{T}_c \quad (1)$$

Where $\dot{\vec{\boldsymbol{h}}}_{\mathbf{c}}$represents the temporal derivation - in the inertial frame of reference - of the angular momentum($\vec{\boldsymbol{h}}_{\boldsymbol{c}}$) relative to the center of mass, $\vec{\boldsymbol{T}}_{\mathbf{c}}$ represents all the torques applied on the satellite (External interfering torqueserodynamic pressure torque, torque of solar radiation, gravity gradient torque). The torques generated by the AOCS actuators are structured in the global angular momentum inertial derivative ($\dot{\vec{h}}_{c}$).

The angular momentum as a function of the angular velocity is given by:

$\vec{\boldsymbol{h}}_{c} = \vec{\boldsymbol{F}}_{b}^{T}\boldsymbol{I}\boldsymbol{\omega}_{bI}$**(2)**

I: the inertia matrix expressed in the satellite reference system**.**

Where $\boldsymbol{\omega}_{bI}$ the angular velocity of the satellite coordinate system **"Fb"** expressed in the inertial coordinate system **"Fi"**.

On the other hand, the inertial derivative of the angular momentum is expressed in the satellite reference system as:

$$\dot{\vec{\boldsymbol{h}}}_{c} = \acute{\vec{\boldsymbol{h}}}_{c} + \vec{\boldsymbol{\omega}}_{bI} \times \vec{\boldsymbol{h}}_{c}\textbf{(3)}$$

$\acute{\vec{\boldsymbol{h}}}_{c}$is the time derivative of the angular momentum in the satellite reference system. Since **"Fb"**is integrated into the satellite then: $\dot{\boldsymbol{I}} = \mathbf{0}$Which leads us to the following expression:

$$\acute{\vec{\boldsymbol{h}}}_{c} = \vec{\boldsymbol{F}}_{B}^{T}\boldsymbol{I}\dot{\boldsymbol{\omega}}_{bI}\ \textbf{(4)}$$

From the last three equations, we can rewrite equation (1):

$\boldsymbol{I}\dot{\boldsymbol{\omega}}_{bi} + \boldsymbol{\omega}_{bi}^{\times}\boldsymbol{I}\boldsymbol{\omega}_{bi} = \boldsymbol{T}_{c}$**(5)**

2.2.2.4.2.Kinematic Equations of the Movement

The orientation of **"Fb"** relative to **"Fi"**- The attitude representation - is configured by the rotation matrix $\boldsymbol{C}_{bI}$. The configuration of this matrix can be done by the use of quaternions (in order not to fall into the state of singular that we mentioned)[5]

$\boldsymbol{C}_{bI} = (2\boldsymbol{q}_{4}^{2} - \mathbf{1})\boldsymbol{I} + 2\boldsymbol{\epsilon}\boldsymbol{\epsilon}^{T} - 2\boldsymbol{q}_{4}\boldsymbol{\epsilon}^{x}$**(6)**

$$\epsilon = \begin{bmatrix} q_1 \\ q_2 \\ q_3 \end{bmatrix}$$

With the index (^{x}) means the following **3x3** dimension matrix (cross-product matrix):

$$\mathbf{if r} = \begin{bmatrix} \mathbf{r}_{\chi} \\ \mathbf{r}_{Y} \\ \mathbf{r}_{Z} \end{bmatrix}; \text{ so: } \mathbf{r}^{\mathrm{X}} \triangleq \begin{bmatrix} \mathbf{0} & -\mathbf{r}_{Z} & r_{y} \\ r_{Z} & \mathbf{0} & -\mathbf{r}_{\chi} \\ -\mathbf{r}_{y} & r_{\chi} & \mathbf{0} \end{bmatrix}$$

The attitude kinematics as a function of the rotation matrix is:

$$\dot{\mathrm{C}}_{bI} = -\mathrm{W}_{bI}^{\times}\mathrm{C}_{bI}(7)$$

Where $\vec{\omega}_{bI}$ the vector describing the angular velocity of the satellite coordinate system **"Fb"** expressed in the inertial coordinate system **"Fi".**

The attitude kinematics expressed in quaternion:

$$\dot{\epsilon} = \frac{1}{2}(q_4 I + \epsilon^{x})w_{bI};\ \ \dot{q}_4 = -\frac{1}{2}\epsilon^{T}w_{bI}\ (8)$$

Equations (5) and (7) fully describe the satellite attitude movement relative to the inertial frame.

2.3.Satellite fault diagnosis

The objective of the diagnostic function is to search for the causes and locate the organs that led to a particular faulty observation. In other words, diagnosis is a procedure that consists of detecting and locating a defective component or element according to the principle of comparing information characteristic of the current state of the system with that established in the absence of faults.

In this section, we will get to know the diagnostic steps first and then we will discuss the classification of faults.

2.3.1. Diagnostic steps

The procedure for detecting and isolating faults goes through three essential stages: Detection, localization, and identification[1]. These steps are summarized in the following figure:

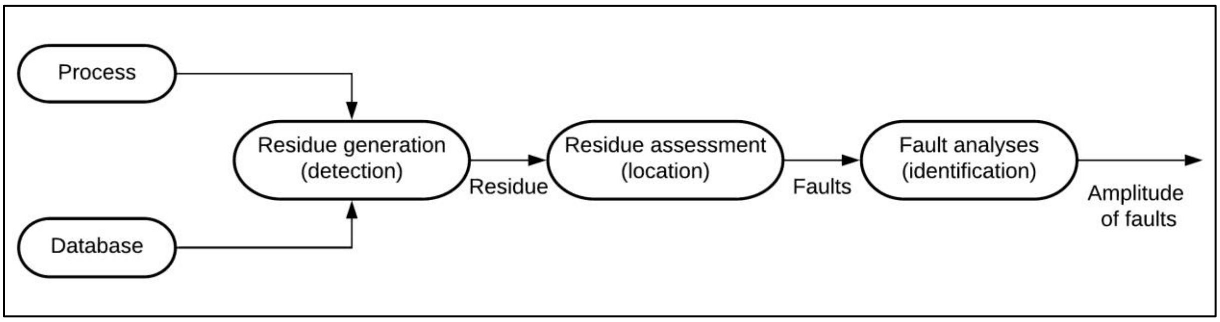

Figure 2.3: Fault detection and isolation procedure

- **Detection**

The objective of the detection procedure is to determine the appearance and the instant of occurrence of a fault. The principle is to compare the behavior of the nominal model of the system with that of the real system, which is to say to determine if the operating state of the system is normal or abnormal, which makes it possible to generate residuals. The quality of detection generally depends on two essential parameters which are false alarm and non-detection. We will talk about the false alarm in detail in the third chapter.

- **Localization**

After detecting the presence of a fault, a localization procedure is used to determine the faulty component or element. This operation is called fault location or isolation.Wespeak of localization when we are, moreover, capable of specifying the nature of the occurring defect(s)

- **Identification**

The objective of the procedure is to identify the actual value of the parameter in default and to estimate the instant of the occurrence of a fault. In addition, the identification may include a procedure to determine the cause of the defect, i.e. its origin.

2.3.2. Classification of faults

When designing a diagnostic system, the first question we ask ourselves is what do we want to detect, i.e. define the type of dysfunction that we want to diagnose. Faults affecting a system can be of different types and are generally classified as actuator faults, sensor faults, and system faults. This is given the locations of defects. Given their temporal properties, they are classified into The biases, Outliers, or Drifts, as also, faults can be classified relative to their effects on system performance, of which two classes of faults can be distinguished: additive faults and multiplicative faults. See [14] [7]. Or classification of faults according to their nature [9]

2.3.2.1.Classification of faults according to their location

As shown in Figure 2.4, faults may manifest in different parts of the system, namely, the actuators, the system, and the sensors. Another type of fault is controller faults and is considered dangerous. See [9]

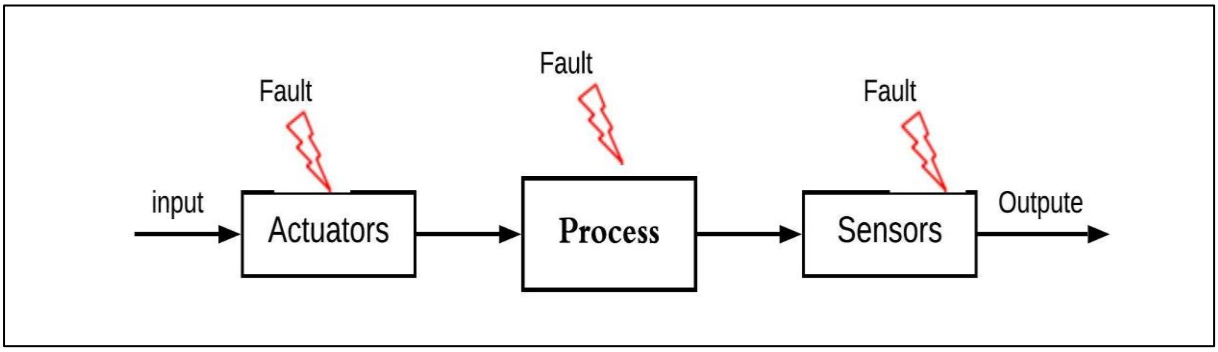

Figure 2.4: Types of faults [14]

2.3.2.1.1. Actuator fault

The actuator faults act on the operative part and thus deteriorate the system input signal. They represent a total or partial loss of the actuator acting on the system. For example in the case of a total loss, when an actuator has remained "sticking" to a position resulting in an inability to control the system utilizing this actuator. Partial actuator faults are actuators that react in a similar way to nominal control but only in part, that is to say with a certain degradation in their action on the system. See figure 2.6 and [9] [11] [12] [13]

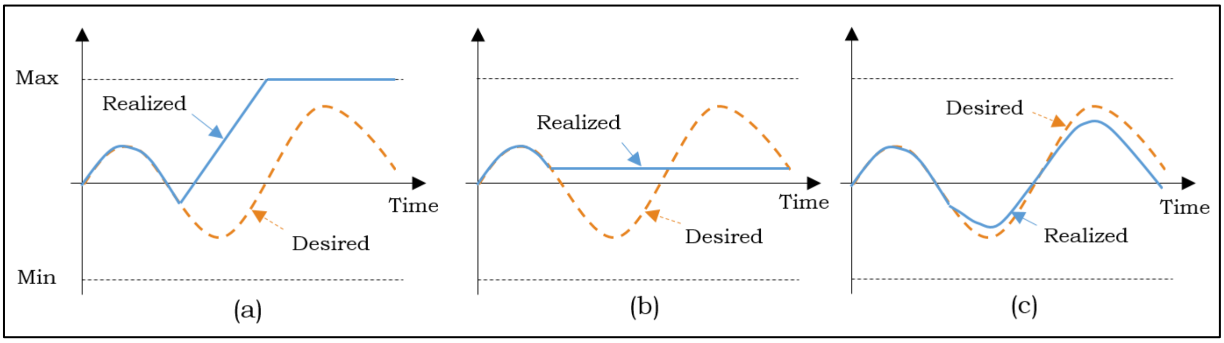

Figure 2.5: Common types of actuator faults

Figure 2.6 describes some actuator faults, where (a) represents hard-over, (b) represents lock-in-place, and (c) represents a loss of efficiency. Hard-over-failure is characterized by the actuator moving to the upper or lower position limit regardless of the command. The speed of response is limited by the actuator rate limit. lock-in-place or freezing the actuator "freezes" at a certain condition and does not respond to subsequent commands. Loss of efficiency has the advantage that the actuator moves to a value slightly less than desired in a positive or negative direction. [11]

2.3.2.1.2.Sensor fault

Sensors are the output interface of a system to the external world and convey information about a system's behavior and its internal states. Therefore, the presence of faults in sensors may deteriorate state estimates and consequently result in inefficient and/or inaccurate control. In figure 2.7 we present some common sensor faults.[9] [11] [13]

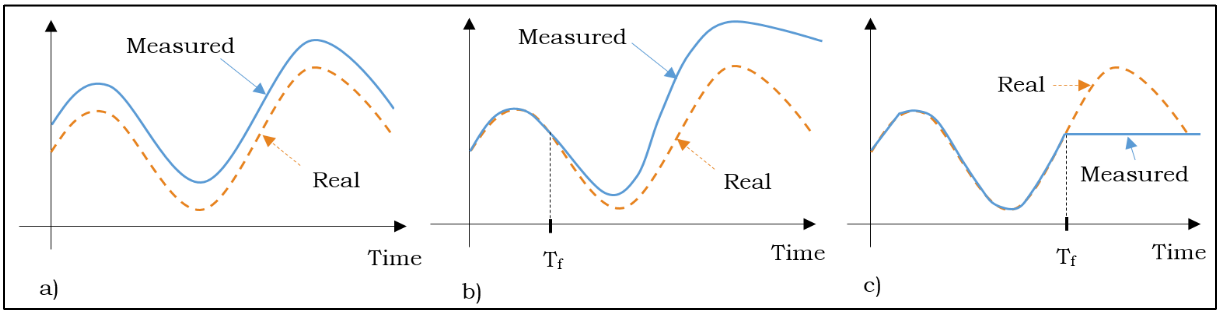

Figure. 2.6: The effect of various sensor faults on system measurements

Figure 2.7 describes some sensor faults, where (a) represents bias, (b) represents drift, and (c) represents Freezing of the sensor. Bias is a constant offset/error between the actual and measured signals. Sensor drift is a condition whereby the measurement errors increase over time (and might be due to loss of sensitivity of the sensor). Freezing of sensor is a sensor providing a constant value instead of the true value. See [11] [12] [13]

2.3.2.1.3.System or component fault

These are faults that appear in the components of the system itself (for example, battery, solar arrays) failures in satellites, that is to say, faults that cannot be classified either among sensor faults or among actuator faults. They represent changes in the parameters of the system, which induces a change in the dynamic behavior of the latter. These faults induce system instability.

2.3.2.2.According to their temporal characteristics

Classification of faults based on their temporal evolution can be divided into three distinct categories abrupt, intermittent, or gradual. See figure 2.6 and [1] [15] [7] [9]

- **Abrupt faults**

A bias - abrupt - is defined as a sharp jump in the signal. it may be a sensor, actuator, or system fault and abrupt faults occur instantaneously often as a result of hardware damage.

- **Intermittent faults**

These are a special case of abrupt faults with the property that the signal returns randomly to its normal value or they are faults that appear and disappear repeatedly, for instance, due to partially damaged wiring.

- **Gradual faults**

A drift is a slow and continuous growth of the fault signal and therefore a progressive deviation from its nominal value. The diagnosis of gradual faults is a challenging task due to the difficulty to distinguish between normal fluctuations of the system and abnormal drift in its operating conditions. Therefore it was necessary to detect a drift in its early stage to provide sufficient time for human operators to achieve appropriate corrective actions to reduce maintenance costs. This type of fault is considered in [9].

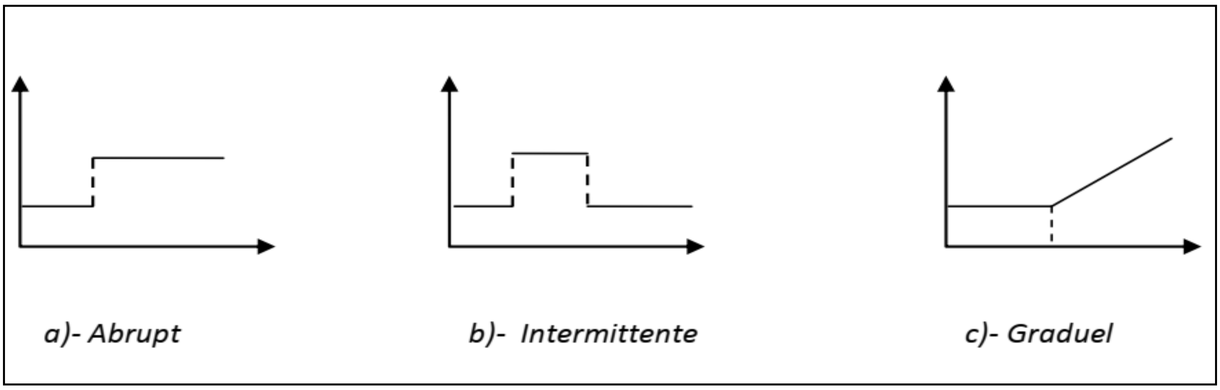

Figure 2.7.: Different types of faults: abrupt, intermittent, gradual fault [1]

2.4. satellite tolerant fault control

The goal of fault-tolerant ordering is to determine an ordering strategy that limits, if not cancels, the effects of a fault on system performance.

2.4.1. Classification of FTC approaches

At first, let's refer to the classification of fault-tolerant control approaches. In general, this classification is based on the effects of the fault on the system, so that, if faults are simple, weak, or already known, then The system deals with it as disturbances, as in this case, we do not need an FDD diagnostic module to detect errors, in this case, we will use a Passive approach (PFTC) that can maintain the required goals with only simple, robust control.But in the case of a critical fault, detection and localization of the latter are necessary to implement an active FTC strategy (AFTC) [14]. The two categories can be summarized in Figure (2.7).

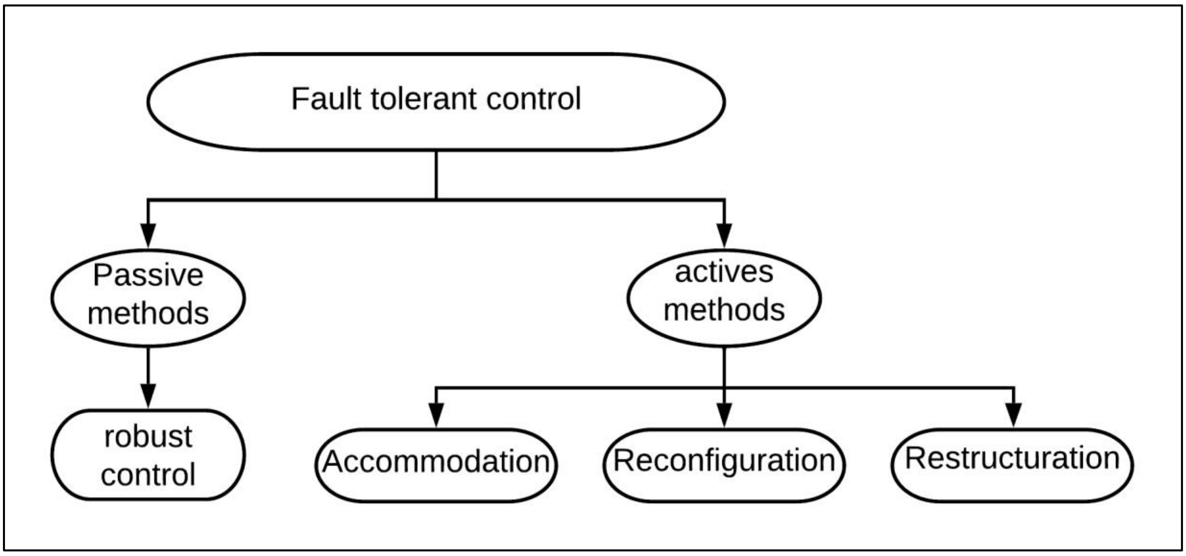

Figure 2.8: Classification of FTC approaches [7]

2.4.1.1.Passive methods

In the passive approach, the control strategies are based on the idea of synthesizing a command allowing the system to be insensitive to modeling uncertainties and certain a priori knew defects. Faults are then taken into account in the design of the control system. The method is based on the simple idea that faults represent disturbances that the control law must take into account from its initial design, therefore no online information on these faults is necessary (No FDD). The major drawback of these approaches lies in the fact that the increased robustness concerning certain faults is obtained at the expense of a degraded performance level under normal operating conditions. In addition, the class of faults considered is limited, it therefore becomes very risky to use passive fault-tolerant control alone. However, in certain applications where the defect class is known and restricted, these strategies may prove to be sufficient [14].

2.4.1.2.Active methods

Unlike passive methods, active fault-tolerant control methods [14] use real-time adjustment techniques by reconfiguring control laws while preserving the stability and performance of thesystem. The use of one of these methods then makes it possible to deal with unforeseen faults but requires an FDD module for detecting and isolating faults capable of also providing precise information on possible faults (instant of pairing, type, amplitude, etc.).It can be summarized as follows:

- **The accommodation of faults:** it acts only on faults of small amplitude. The new control law is generated by the online adaptation of the regulator parameters and the system inputs/outputs, without modifying the structure of the system.
- **System reconfiguration:** it is used if the failing parties cannot be accommodated. It is characterized by the modification of the inputs/outputs between the control law and the system to be controlled through a change in the parameters and the structure of the control law.
- **Restructuring:** it consists of synthesizing a new control law by modifying its structure and parameters.

2.5.The objective of this work

A fault-tolerant system has the capacity to maintain nominal targets despite the occurrence of a fault and to deal with it automatically. In particular, it guarantees the stability of the system and / or acceptable performance in the presence of faults. Even though a classical control scheme makes it possible to guarantee the desired stability and performance of the system in the nominal case, it turns out to be very limited and can guide the system towards uncontrolled behavior, or even instability, in the presence of a fault. To overcome such shortcomings, specific control laws, taking into account the effect of the fault, have been developed with the specific aim of protecting the desired performance.

Since the Algerian satellite ALSAT-2 uses different sensors- One of the most important is the gyroscope which calculates the angular velocity - for attitude determination, and actuators for attitude control. We chose to study FTC/FDD with faults affecting the angular velocity sensor(gyroscope) as the objective in our thesis. Let's inject him a fault, then let's automatically detect the fault, which is the 1st step of active FTC which is FDI, which is what we will focus on in this thesis, to facilitate the steps later.

2.6.conclusion

This chapter can be summarized by summarizing the FTC and FDD steps, as they consist of four steps, The first step aims at fault detection (To indicate the presence of a fault.). The second step is determining the exact fault's location (The fault is in gyroscope x, y, or z). The third step is to try to figure out the amplitude of the fault (The identification of faults.), The last step is Step correcting fault (FTC or Reconfiguration). The first three steps represent the FDD diagnosis, while the last step represents the FTC.

Chapitre III : Proposed approach for fault tolerant control ADCS

3. Proposed approach for fault tolerant control of ADCS

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3.1. Introduction

The attitude sensing function is mission-critical as the failure of this function will lead to the wrong control signal generated by the AOCS controller. This could harm some of the devices in charge of a mission. Thus, you will lose the most important functions, so it is a good idea to start this chapter with challenges and motivations to discuss this thesis. Let's explain secondly, the proposed approach with a discussion of all stages, to present at the end the model used, and the obtained results.

3.2. Challenges and motivations

As stated earlier, the purpose of ADCS is to determine the orientation of the satellite concerning some reference frame. This requires the measurement of various vector quantities in the body frame of the satellite. This task is performed by sensors- gyroscope and SST in ALSAT-2 - which will take a "heartbeat" of the attitude of the satellite or like eyes and ears of the satellite., which the processor will then interpret into a set of coordinates relative to a reference frame.

Once the position and orientation (attitude) has been calculated, the satellite may need to re-position to face a particular direction, such as pointing the solar panels towards the sun for recharging, or pointing the camera at the desired coordinate on earth to take exact pictures at a specific time, for example - which is the task assigned to ALSAT-2, the satellite will need to actuate into a position such that the camera is directed at the earth by the time it passes over those coordinates; furthermore, it will require a high pointing accuracy in a short period of time. This in itself is a challenge to the accuracy of the sensors in determining the desired attitude, furthermore, the control center sends instructions to the satellite in the form of a plan (a sequential form of instructions). There are other challenges that we will talk about, such as false alarms and satellite autonomy.

Satellite maintenance and repair of faults that may affect some parts of it is an important step that we need to maintain the performance of this system (satellite), and increase its life span, for this maintenance process, if it were on the ground level and a static system would have been familiar, but we are talking about maintenance For a satellite orbiting with a fast velocity at its orbit, which is (Low Earth Orbit (LEO), for example, ALSAT-2B has a speed of 7 km / s, so how can we stop, repair and maintain this system!?For this reason, recent research tends to work to extend the life of existing satellites In space instead of launching expensive new satellites, this is a very difficult approach, but there is another direction which is what we’re dealing with in this work, which is the trend towards satellites that fit themselves to enjoy these satellites with autonomy - for example, ALSAT-2B designers headed this direction when they put four reaction wheels instead of three for example.

In faults-free nominal operating conditions, in general, residues are equal to zero and differ from zero when faults are present. But in some cases, it differs from zero, but it is not with faults such as the noise or disturbances or uncertainties, as this situation is not considered as normal and is not considered a failure either, which is called a false alarm.

A false alarm is an indication of the existence of a fault when a fault does not occur in reality or is a false notification of an emergency which necessitates generating orders without reason so that these alarms become annoying to the FDD system that cannot be diagnosed or detected - such as intermittent faults that lead to an event called " Not fault found "- correctly. A threshold is usually placed to avoid these false alarms, and if the residues signal crosses the threshold the alarm is correct. There are other ways to identify and control false alarms and can be found in [9]

3.3. Proposed approach with a discussion of all stages

In this section, the ADCS loop was developed by a database to achieve a state and fault monitoring such as fault detection of a sensor (gyroscope). It performs predictive diagnostic by detecting deviation of a system operating conditions from normal to faulty mode. The proposed approach is based on 2 steps developed in the following subsections.

3.3.1. Processing and data analysis

This step aims at finding the features that are sensitive to the system operating conditions to construct the feature space. A feature space representing the operating conditions of each gyro x, y, and z, this feature space will be responsible for the detection and localization of faults impacting those gyroscopes. The research of sensitive features is based on the signals provided by the sensors. These features are chosen to maximize the discrimination between operating conditions in the feature space. In this chapter, the three-dimension feature space is constructed. The goal of the feature space use, at the level of component, is to facilitate the fault isolation and to enhance the diagnosis robustness. [8] [9]

This feature space is a residual calculated by equation (3.1), (3.2), (3.3)

$$\mathbf{R}_{\mathbf{x}} = \mathbf{Q'}_{\mathbf{SSTx}} - \boldsymbol{W}_{\mathbf{gx}} \qquad \mathbf{(3.1)}$$

$$\mathbf{R}_{\mathbf{y}} = \mathbf{Q'}_{\mathbf{SSTy}} - \boldsymbol{W}_{\mathbf{gy}} \qquad \mathbf{(3.2)}$$

$$\mathbf{R}_{\mathbf{z}} = \mathbf{Q'}_{\mathbf{SSTz}} - \boldsymbol{W}_{\mathbf{gz}} \qquad \mathbf{(3.3)}$$

Where $\mathbf{Q'}_{\mathbf{SST\ x}}$and ,$\mathbf{Q'}_{\mathbf{SST\ y}}$and $\mathbf{Q'}_{\mathbf{SST\ z}}$are time derivatives of the angles measured by SST with respect to the x, y, and z-axis respectively. And $\boldsymbol{W}_{\mathbf{gx}}$and ,$\boldsymbol{W}_{\mathbf{gy}}$and $\mathbf{W}_{\mathbf{mz}}$are angular velocities measured by gyroscopeswith respect to the x, y, and z axis respectively.

Not all sensors have the same credibility as there is a discrepancy between them, so there is a sensor that gives measurements in which errors are made and there is less error than it or in other words reliable on the other. Based on this, the residue generation was chosen based on the angle measured by the SST, that is, we put more credibility in the SST than the gyroscope - moreover that from the angular velocity estimations the derivation of the SST measurements - and based on the difference between the derivative of the SST measurements and the gyroscope measurements we can conclude If the residue is equal to zero, then the measurements are correct, and if they differ from zero with a certain value, then the measurements are wrong. In other words, when the Gyroscope is mistaken we will monitor and detect it with SST. This is practically present in the space industry as they place more than one sensor to make the system reliable.

In the feature space, when injecting three faults - a fault with an amplitude of 0.0004 per X, Y, and Z gyroscopes - we will notice that the faulty class is oriented towards the axis to which we added the fault. (See Figure 3.1, Figure 3.2 and Figure 3.3).

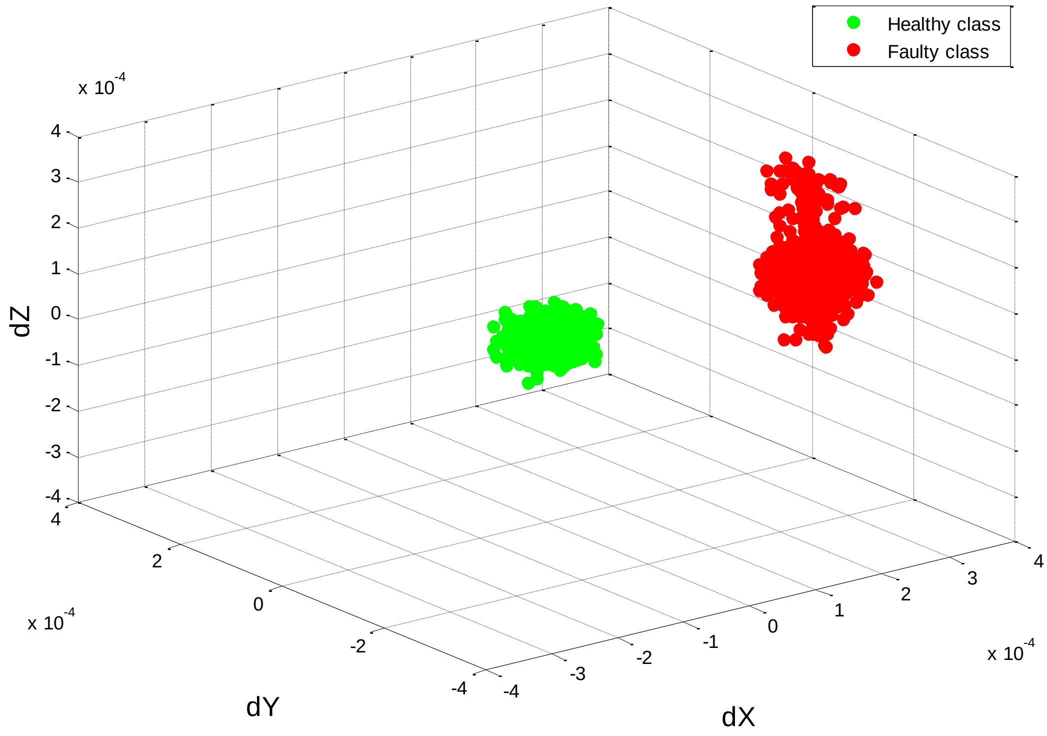

Figure 3.1: Feature space display showing normal operating conditions and failure mode for gyro x

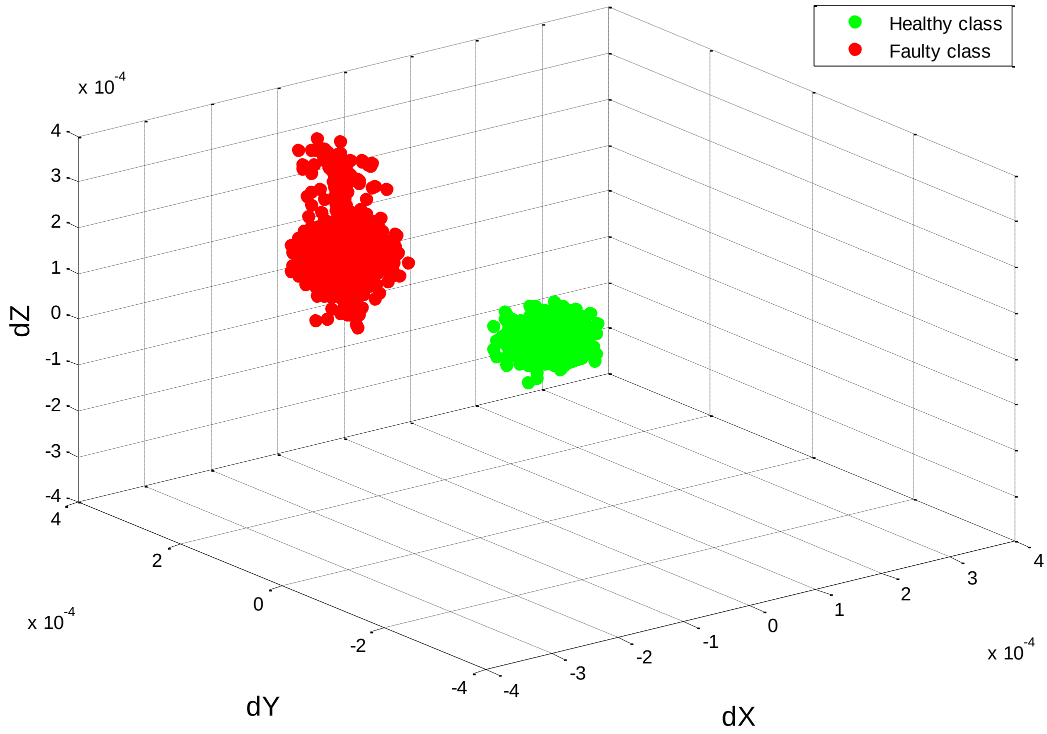

Figure 3.2: Feature space display showing normal operating conditions and failure mode for gyro y

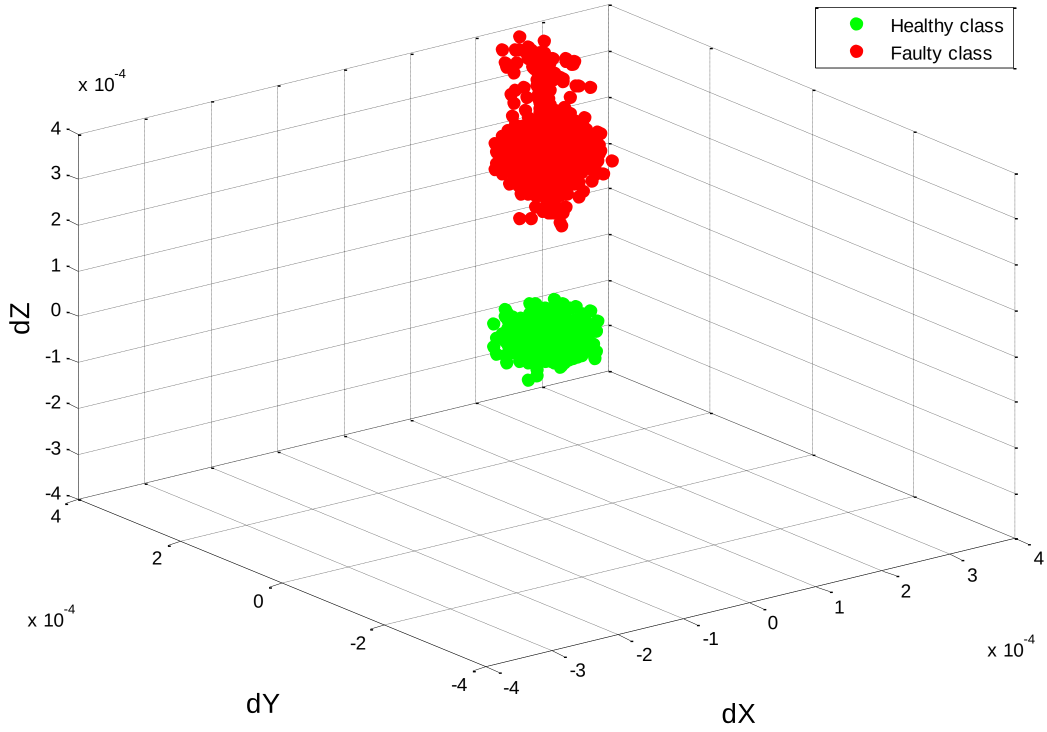

Figure 3.3: Feature space display showing normal operating conditions and failure mode for gyro z

3.3.2. Fault monitoring and interpretation

The gyroscope sensor can give faults with its real measurements so that these faults affect the loop controlling the attitude of satellite, and these effects can exceed the impact on the attitude control system to be dangerous on the satellite itself as happened with the Japanese Hitomi satellite [19] [20] with its gyroscope fault led to an uncontrolled rotation rate for the satellite to eventually disintegrate. To guard against this and avoid reaching such dangers, early detection of the fault should be allowed, allowing operators to allocate more time to perform maintenance procedures. To this end, the design of a classifier aimsat building a decision function in order to separate the different classes (i.e., representing normal and failure operation modes) in the featurespace. The current operation conditions are represented by a point in the feature space. The classifier'sdecisionfunction assigns this point into one of these classes allowingto determine if the system is in normal or failure operation mode. When a new failure mode occurs, the classifier's decision function must be updated in order to integrate this new failure mode (i.e., represented by a new zone or class in the featurespace). Without loss of generality, the Auto-adaptive Dynamical Clustering (AuDyC) method [11] is used in order to design the classifier and update its decision function's parameters and structure. The classifier's design and update are based on the statistical properties (data distribution in the feature space represented as a Gaussian mixture) of the initial data samples forming the initial classes. It is unsupervised classification method able to learnthe initial classes' parameters (gravity center, variance–covariance matrix) and update them online. Each class isrepresented by itsgravity center μPj∈ Rd and a variance–covariance matrix ΣPj∈ Rd×d in a feature space of d features. Each class requires a minimum number Nwinof points defined by users. The update of each class' parameters is achievedby integrating the new incoming points and removing the oldestones through a sliding time window.

Health indicator

The health indicator aims at measuring the dissimilarity between the normal class C_n and the evolving class C_e. This dissimilarity is represented by the distance between the gravity centers μn and μe of the normal C_n and evolving C_e classes [8]. The gravity center μe is updated online after the reception of each new incoming point X_{new}. Then, the health indicator I_E (X_{new}) is calculated to take into account this new incoming point xnew. I_E (X_{new}) is calculated as the distance between:

$$\mathbf{d_E(\mu_n, \mu_e) = \sqrt{(\mu_{n,x} - \mu_{e,x})^2 + (\mu_{n,y} - \mu_{e,y})^2}} \quad \mathbf{(3.4)}$$

whered_E is the euclidean metric. The coordinates (μ_n,x, μ_n,y) and (μe,x, μe,y) are the projection of μ_n and μe respectively in the system coordinate. The indicator I_E (X_{new}) keeps always the greatest distance over time [8]. Therefore, I_E (X_{new}) will be calculated as follows:

$$\mathbf{I_E(X_{new})} = \begin{cases} \mathbf{d_E(X_{new}) if d_E(X_{new}) > d_E(X_{t-1})} \\ \mathbf{d_E(X_{t-1}) otherwise} \end{cases} \qquad \textbf{(3.5)}$$

To avoid false alarms, a fault is detected and confirmed when I_E becomes greater than the chosen threshold (equals to 3.10^{-4}in in this case). This threshold allows us to obtain a trade-off between false alarms and missed alarms.

3.4. Experimentation and results obtained

Before presenting the results obtained, it is a good idea to present the model used in this thesis and to present some important blocks

3.4.1.Representation of AOCS model

We'll start by viewing the global model from abroad. The value we want to control is the satellite attitude (pointing angles). Next, we show the dynamic satellite model that has as output the measured angular velocity - and this value is the one that the gyroscope sensor measures - its name is Wbo (t) in the model where we added noise to it to be closer to the real sensor measurements, and the output measures the angle (using the attitude kinematics). Let's show after this block, residual generator, we finally end with a display of the suggested reference signal.

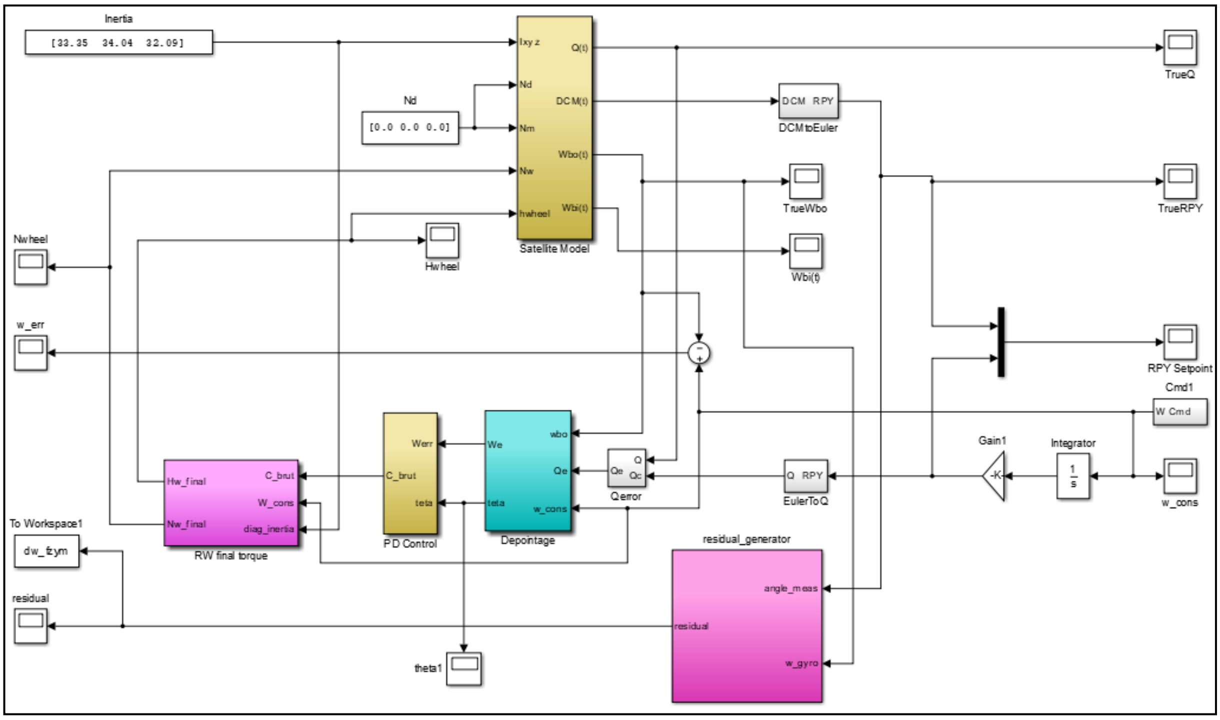

Figure 3.4: The Attitude simulator

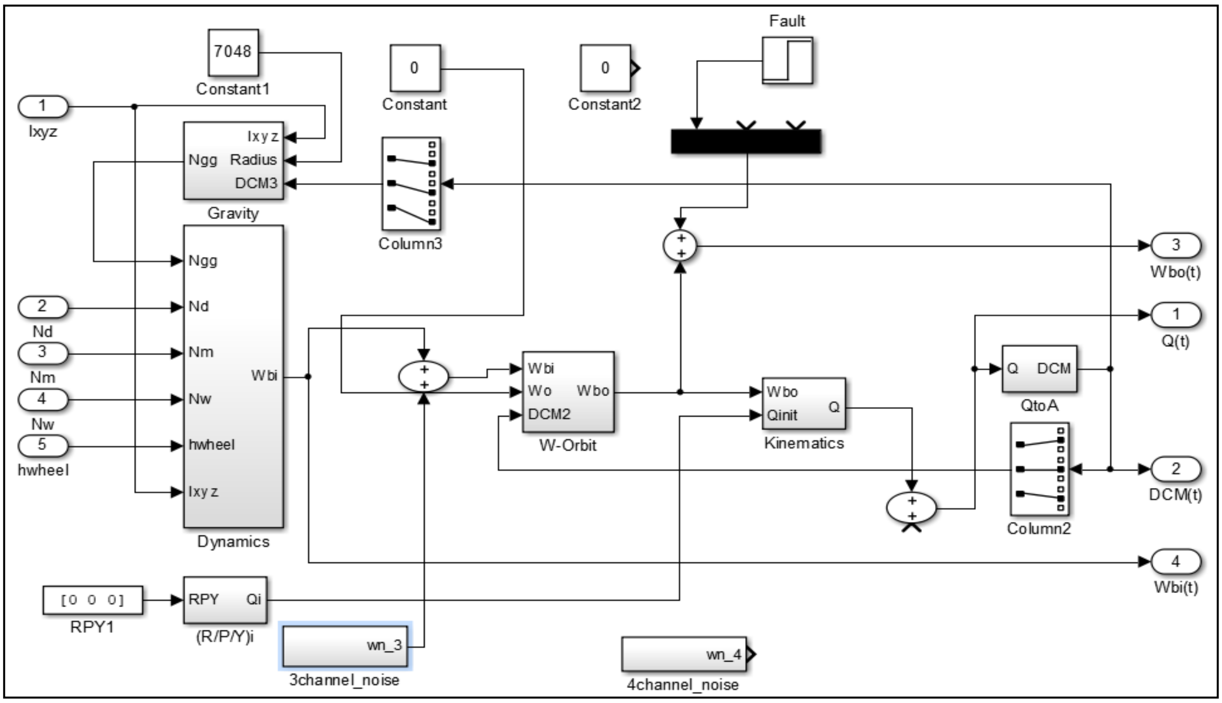

Figure 3.5: Subsystem « satellite model»

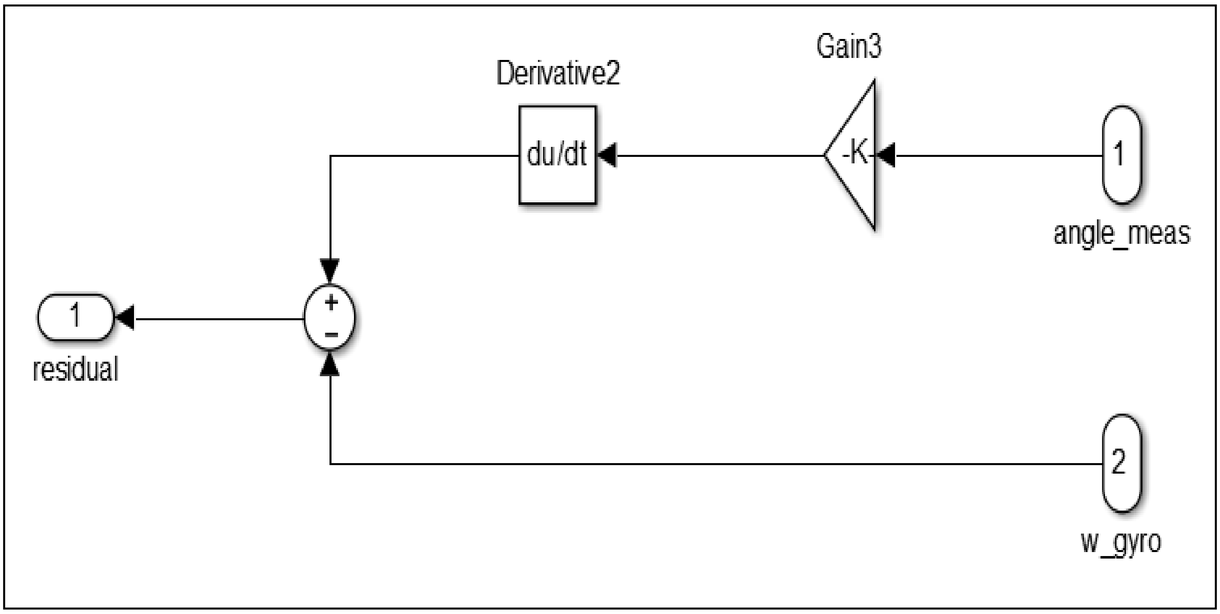

Figure 3.6: Subsystem «residual generator»

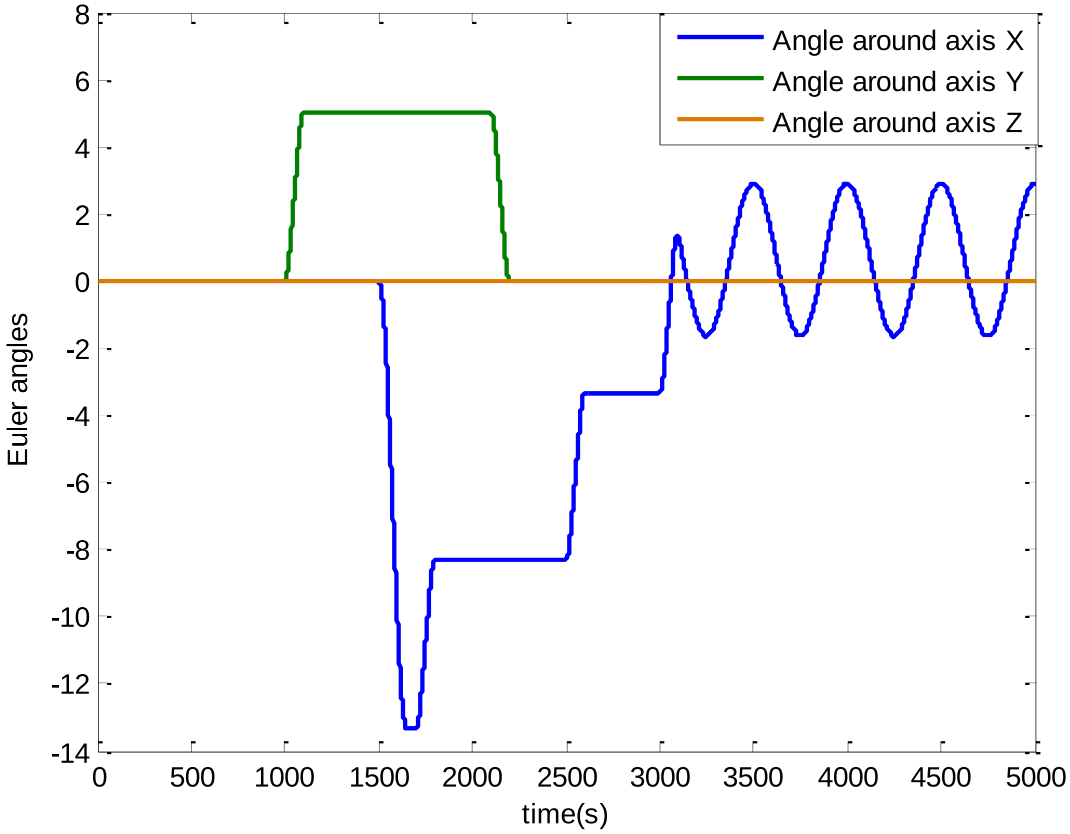

Figure 3.7: Display of the reference signal of attitude

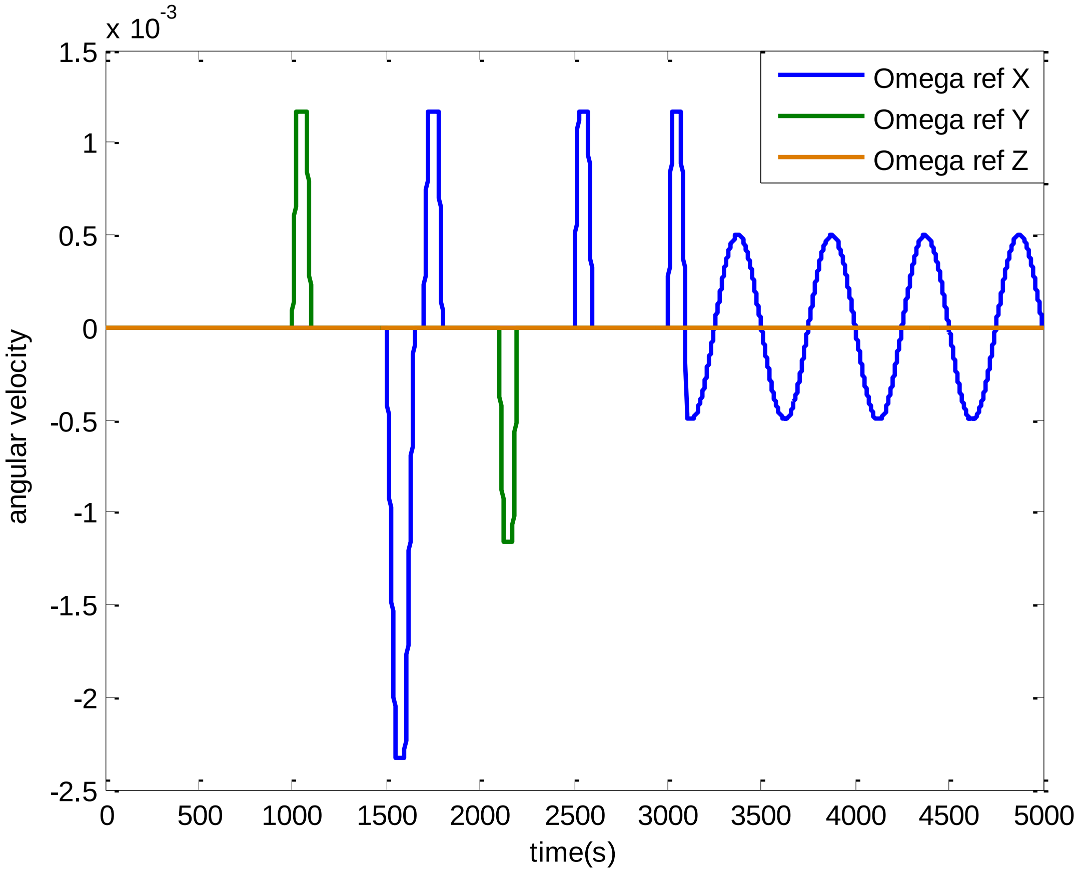

Figure 3.8: Display of the reference signal of angular velocity

3.4.2 Present and discuss results

First, we will present the residues obtained after injecting three faults - with different amplitudes A1 = 4.10^{-4} then A2 = 6.10^{-4}then A3 = 7.10^{-4}- for the X axis over time T1 = 1400 ms, and the same amplitudes of previous faults for the Y axis but with a change in time T2 = 2500 ms. Let us display after each residu a health indicator that can detect the error automatically**.**

	Thefaulty sensor	**Amplitude offault**	**Period of fault**
First residual	**Gyroscope X**	$\mathbf{4.10^{-4}}$	**1400 S-5000 S**
Second residual	**Gyroscope X**	$\mathbf{6.10^{-4}}$	**1400 S-5000 S**
Third residual	**Gyroscope X**	$\mathbf{7.10^{-4}}$	**1400 S-5000 S**
Fourth residual	**Gyroscope Y**	$\mathbf{4.10^{-4}}$	**2500 S-5000 S**
Fifth residual	**Gyroscope Y**	$\mathbf{6.10^{-4}}$	**2500 S-5000 S**
Sixth residual	**Gyroscope Y**	$\mathbf{7.10^{-4}}$	**2500 S-5000 S**

Table: Information on fault amplitude and fault period for the six fault scenarios.

3.4.2.1.Results display

3.4.2.1.1.X-axis faults

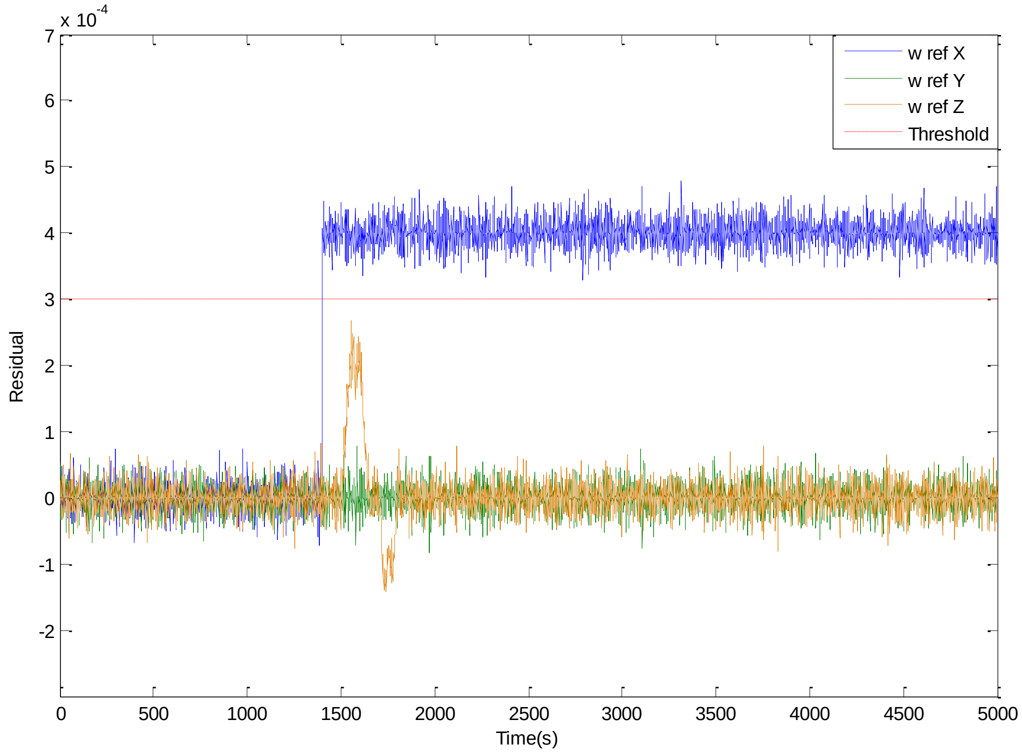

Figure 3.9: The first residual carries a simple "additive" fault in gyroscope X

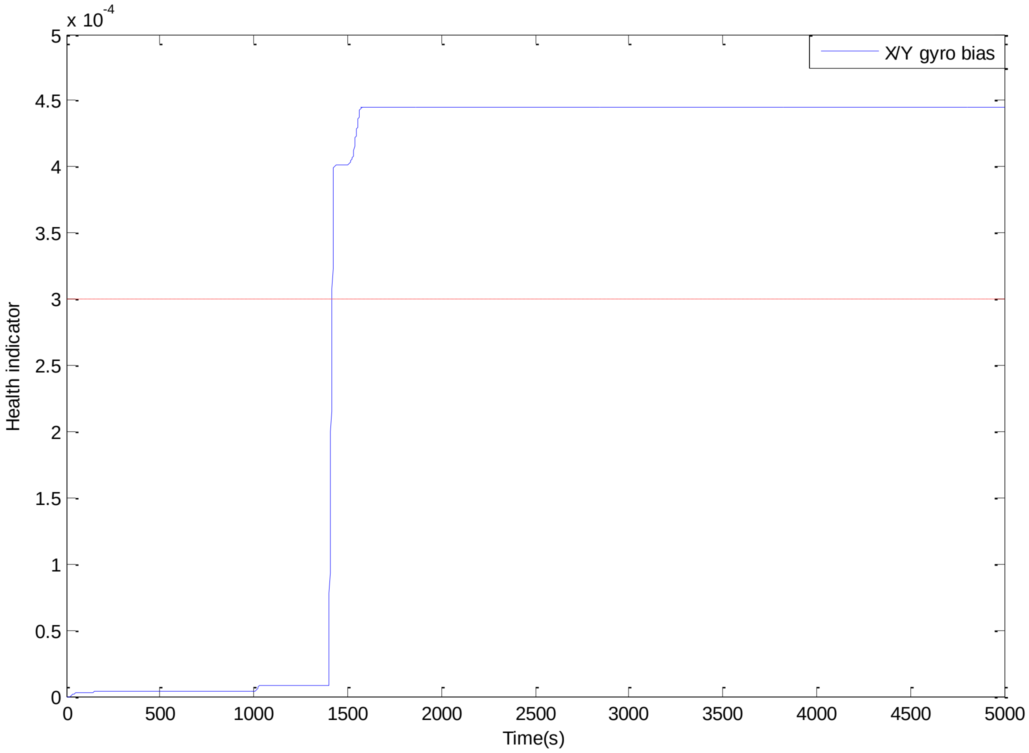

Figure 3.10: First fault detection by health indicator at 1400 s with an amplitude of 0.0004 in gyroscope X

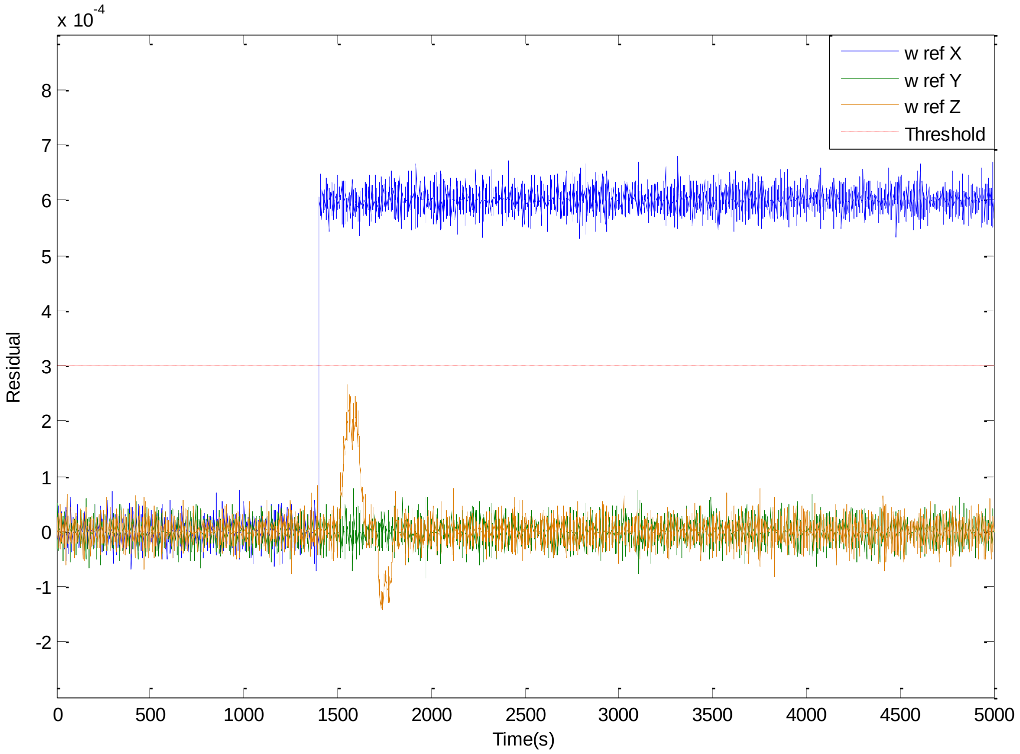

Figure 3.11: The second residual carries a simple "additive" fault in gyroscope X

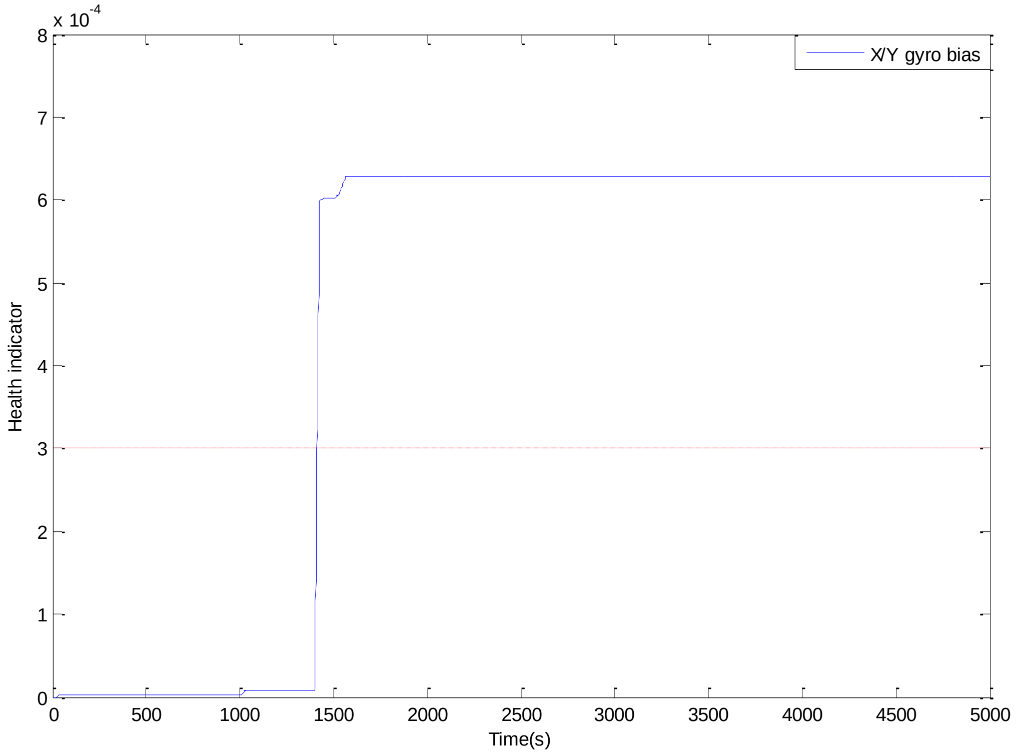

Figure 3.12: Second fault detection by health indicator at 1400 s with an amplitude of 0.0006 in gyroscope X

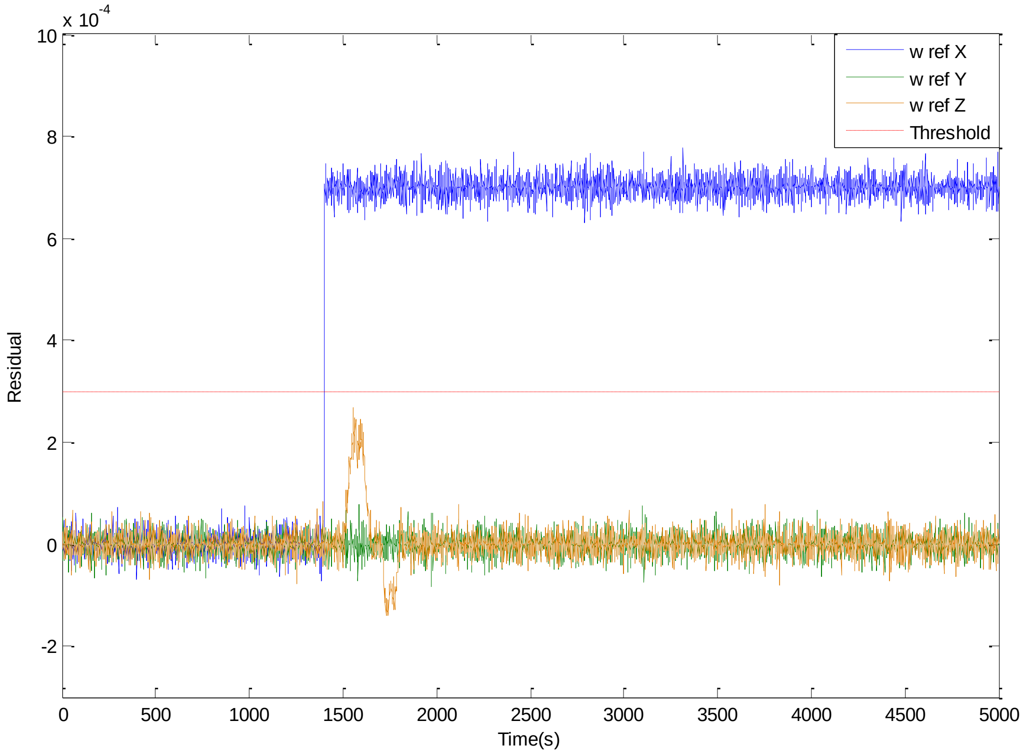

Figure 3.13: The third residual carries a simple "additive" fault in gyroscope X

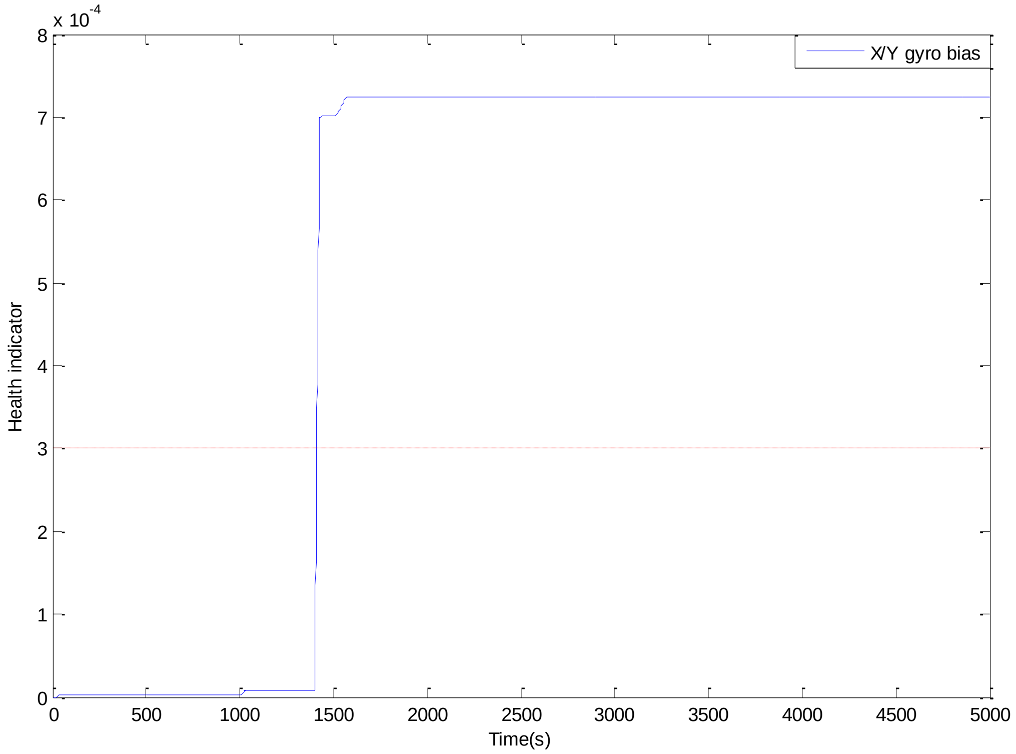

Figure 3.14: Third fault detection by health indicator at 1400 s with an amplitude of 0.0007 in gyroscope X

3.4.2.1.2.Y-axis faults

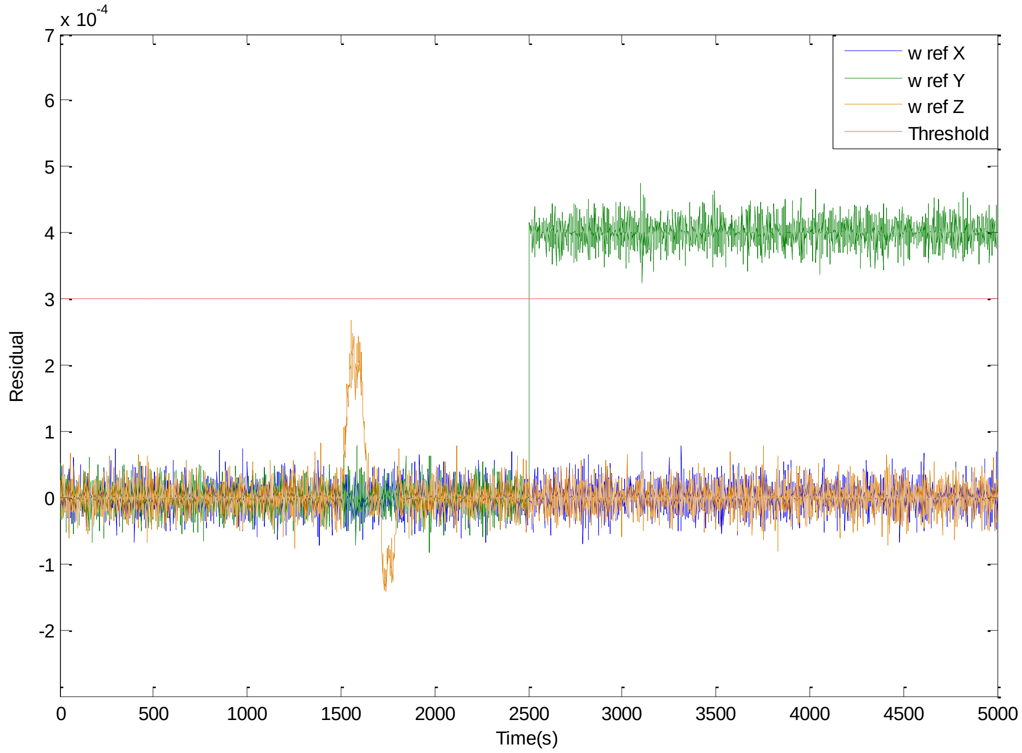

Figure 3.15: Fourth residual carries a simple "additive" fault in gyroscope Y

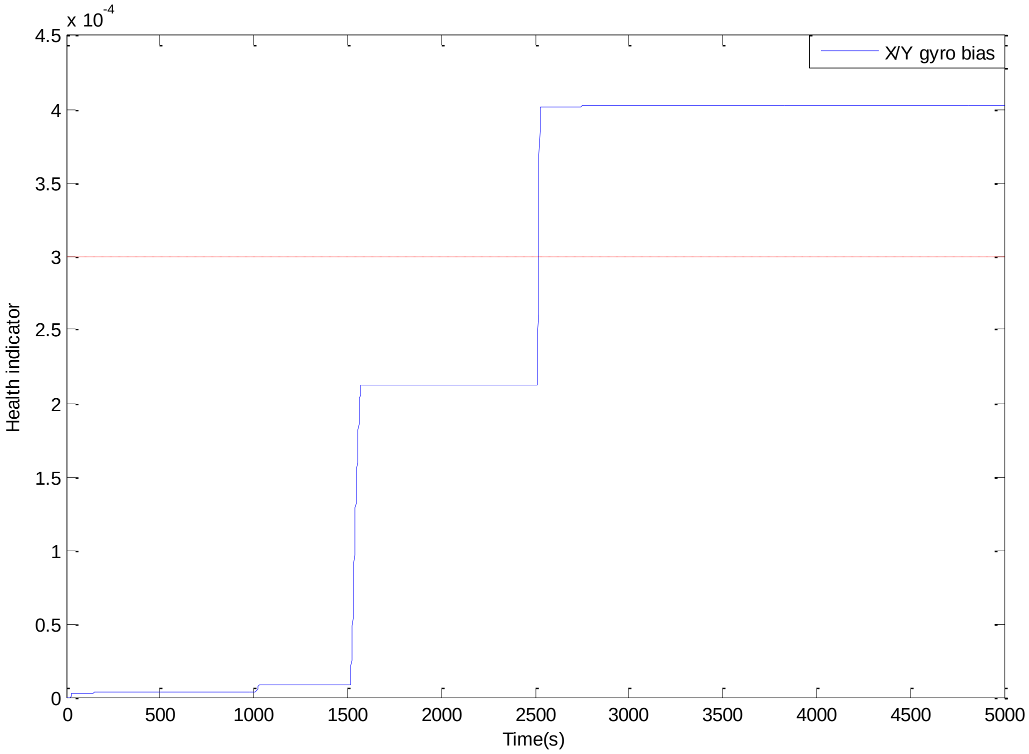

Figure 3.16: Fourth fault detection by health indicator at 2500 s with an amplitude of 0.0004 in gyroscope Y

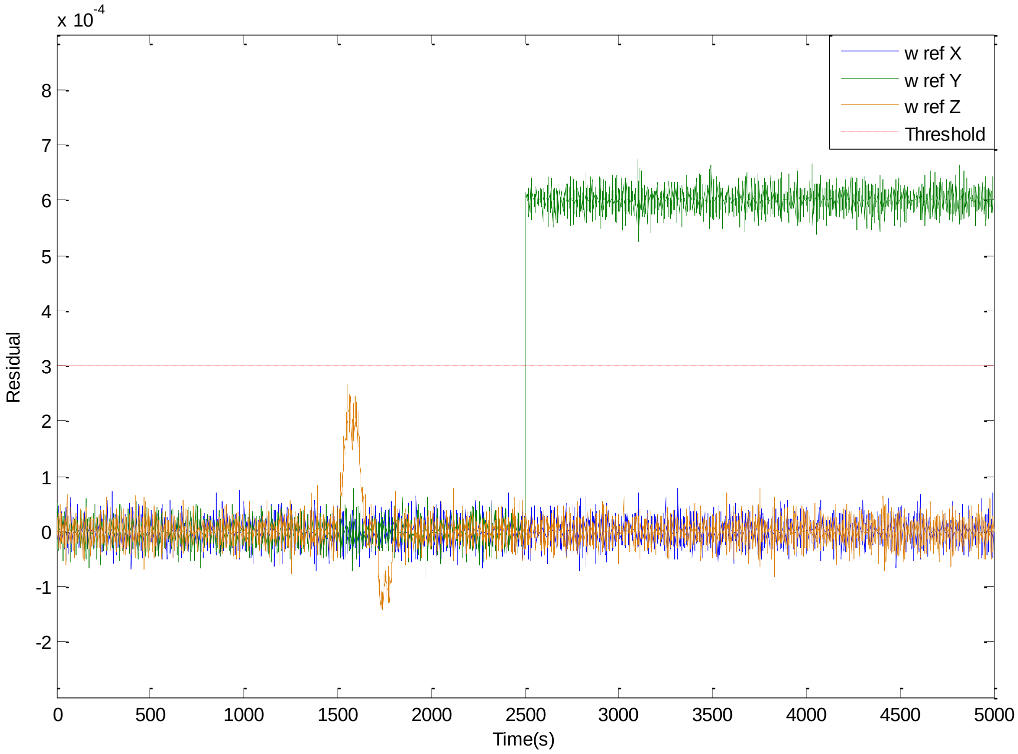

Figure 3.17: Fifth residual carries a simple "additive" fault in gyroscope Y

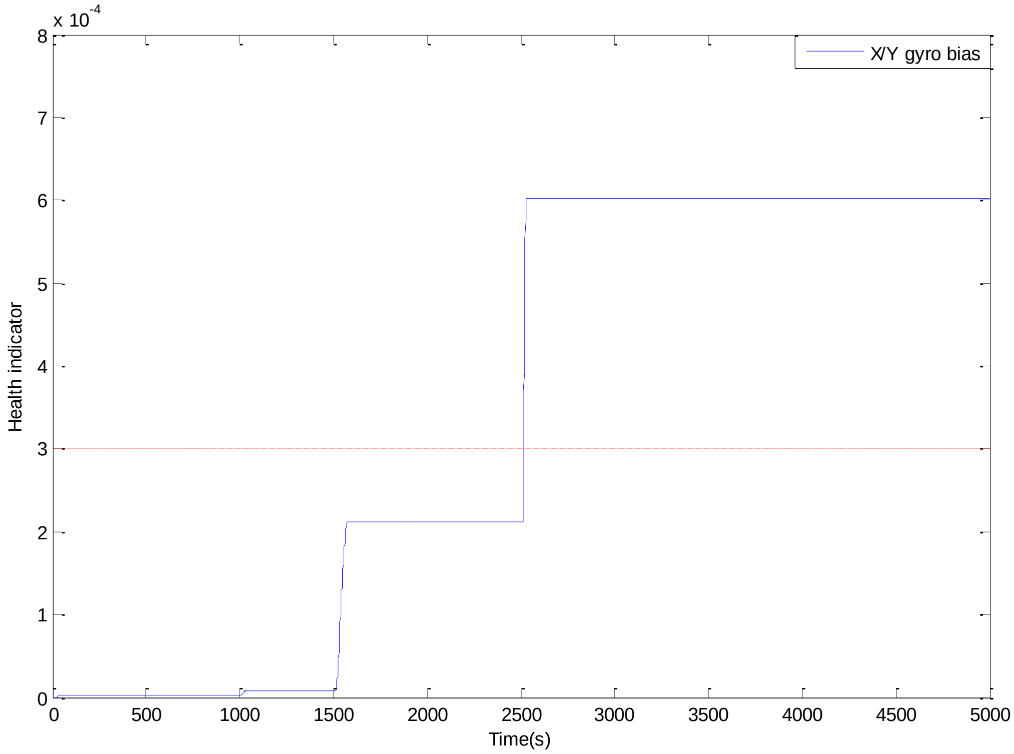

Figure 3.18: Fifth fault detection by health indicator at 2500 s with an amplitude of 0.0006 in gyroscope Y

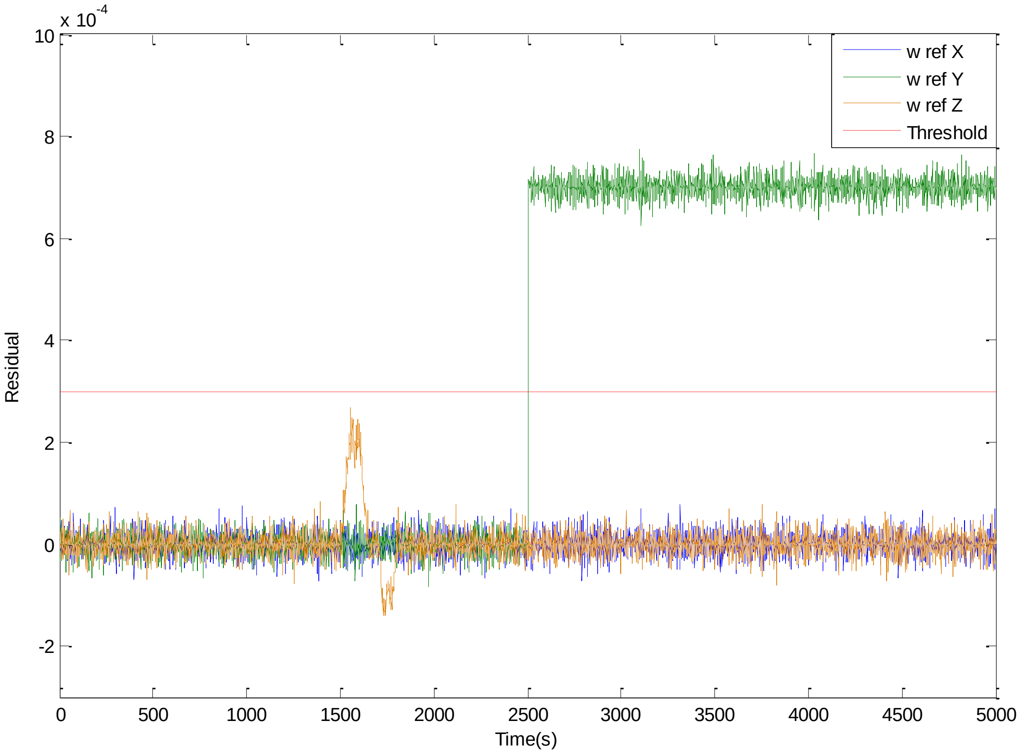

Figure 3.19: Sixth residual carries a simple "additive" fault in gyroscope Y

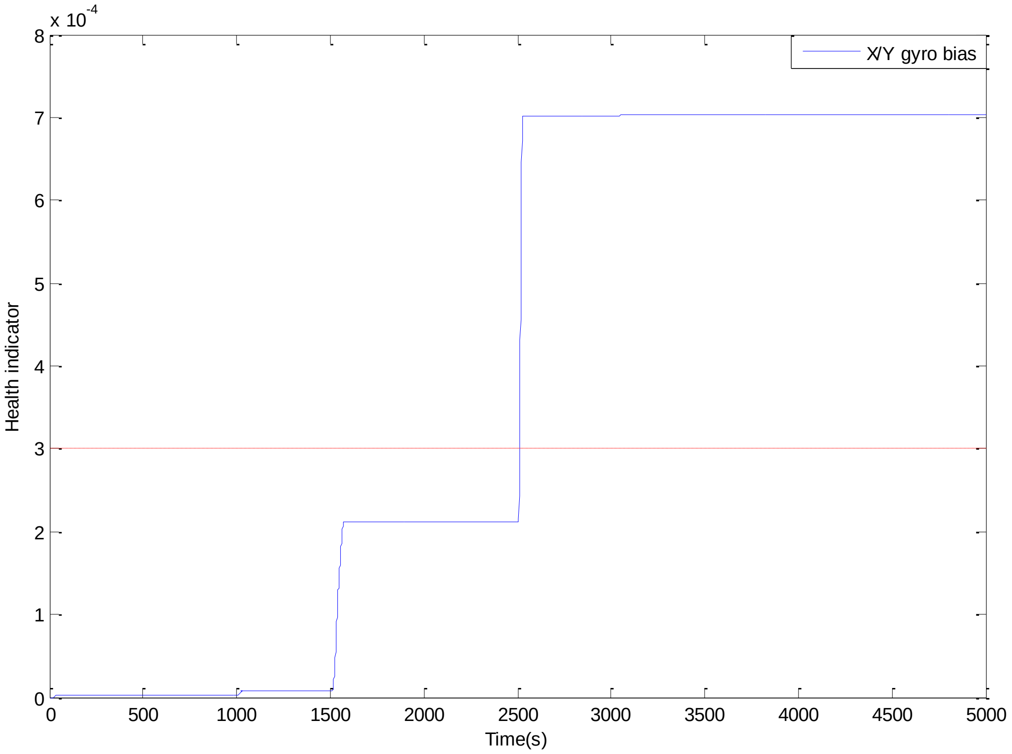

Figure 3.20: Sixth fault detection by health indicator at 2500 s with an amplitude of 0.0007 in gyroscope Y

3.4.2.1. Discussion of results

Through the foregoing and results obtained, we notice when injecting any fault, the residual signal rises above zero, indicating the occurrence of the fault, anda change in the residual is observed around 1500 sec, this is directly related to the closed-loop control response which is the normal behavior of the system. therefore, we see clearly the benefits of using the threshold, namely avoiding the false alarms that could be raised by such nominal dynamics.We also note that the health indicator reveals a fault after each residual differs from zero with a value greater than the threshold and that detection by the health indicator gets after the residuals value rises above zero directly, which confirms the accuracy of the indicator in the early detection of the error and is the most important thing for us, as the detection of fault is the first step in the FDD so that the next steps are based on it, especially since residuals is made up of other sensor measurements, which confirms the reliability, effectiveness, and strength of the diagnostic system and the resulting residuals the best evidence for this.

3.5. Conclusion

One of the most important things we did in this chapter is to observe the gyroscope sensor with another sensor, which is SST, by injecting faults of the value measured by the gyroscope so that we can obtain residues that differ from zero and exceed the threshold, to suggest in the last an algorithm that automatically detects a fault.

Chapitre IV : General conclusion and perspective

4.General conclusion and perspective

4.1.Summary of contributions and discussion..40

4.2.Perspectives 40

4.1.Summary of contributions and discussion

The faults that impact the gyro sensor affect the attitude control loop and the stability of the system in general so that the error of the gyroscope can lead to dangerous things like directing the camera to the sunlight while it is operating, so the camera fails and the satellite loses its main task which is to take images...So in this thesis, we suggested a Fault Detection and Diagnosis strategy for the gyroscope that can maintain desired targets when a fault occurs in one of the axes so that this strategy works to detect the fault and determine its location and the knowledge of its amplitude, to perform afterwards the FTC reconfiguration.

4.2.Perspectives

The development of the ADCS system is a topic of active and interesting research, as all research about making satellites more independent and making them more flexible to self-repair when an error occurs to maintain the required performance and to increase its operating life. To this end and throughout the development of this work, several extensions are possible to enrich the proposed scheme. It is possible to search for the possibility of more than one fault at the same time (for example on the X and y-axis) and try to detect and diagnose it and the possibility of automatically determining the fault amplitude for and perform an adequate FTC reconfiguration.

Bibliographie

[1] ACHBI Mohammed Said. Commande tolérante aux défauts en utilisant les Réseaux de Neurones Artificiels et les Systèmes d'Inférence Floue. Biskra 2012.

[2] CEREN KAPLAN. LEO SATELLITES: ATTITUDE DETERMINATION AND CONTROL COMPONENTS ; SOME LINEAR ATTITUDE CONTROL TECHNIQUES.MIDDLE EAST TECHNICAL UNIVERSITY 2006.

[3] DánielBolgár, Nikolaos Biniakos, Alexandru-Cosmin Nicolae. Fault Tolerant Attitude Control of a Pico-Satellite Equipped with Reaction Wheels and Magnetorquers. Aalborg University Control & Automation Fredrik BajersVej 7 DK-9220 Aalborg. 07/06/2018.

[4] HARRATS Fayssal. Estimation d'Attitude Globale d'un Microsatellite à Basse Altitude par le Filtre de KALMAN. UNIVERSITE DES SCIENCES ET TECHNOLOGIE D'ORAN. 2012.

[5] Mme BELMAHI HAKIKI Saliha. MODELISATION ET SIMULATION DU CONTROLE D'ATTITUDE D'UN SATELLITE SUR SON ORBITE. Université des Sciences et de la Technologie d'Oran 2010.

[6] Damaren Cristopher et al. Spacecraft dynamics and control: an introduction, pp 223-225. Wiley 2013.

[7] BOUGUERRAAbderrahmen. Commande Tolérante aux Défauts d'un Appareil à Vol Vertical. UNIVERSITE MOHAMED BOUDIAF DE M'SILA. 2015.

[8] H. Toubakh, M. Sayed-Mouchaweh, M. Benmiloud et al., Self adaptive learning scheme for early diagnosis of simple and multiple switch faults in multicellular power converters. ISA Transactions (2020), https://doi.org/10.1016/j.isatra.2020.03.025.

[9] TOUBAKHHouari. Automated On-line Early Fault Diagnosis of Wind Turbines Based onHybridDynamic Classifier. DOUAI ET L'UNIVERSITE DE LILLE 1. novembre 2015.

[10] Dimitri Peaucelle et al. Robust analysis of Demeter benchmark via quadratic separation. Jan 2010.

[11] SALOWA METHNANI .Diagnostic, reconstruction et identification des défauts capteurs et actionneurs : application aux station d'épurations des eaux usées. Université de Sfax École Nationale d'Ingénieurs de Sfax. 17 Décembre 2012.

[12] HalimAlwiand Christopher Edwards, Chee Pin Tan. Fault Detection and Fault-Tolerant Control Using Sliding Modes. Springer. 2011.

[13] M. Thoma, F. Allgöwer, M. Morari.Fault Diagnosis of Nonlinear Systems Using a Hybrid Approach. Springer. 2009.

[14] IKNI Samir. Diagnostic de Pannes et Commande Tolérante Aux Fautes D'un Robot Manipulateur Télé-Opéré. UNIVERSITE DE BATNA. 2011.

[15] Godard. FAULT TOLERANT CONTROL OF SPACECRAFT. Ryerson University. 2006.

[16] AlSat-2B. spaceflight101.com. The site has been viewed April 2020.

[17] AlSat-2 (Algeria Satellite-2). directory.eoportal.org. The site has been viewed April 2020.

[18] *This article is part of the NASA Knows! (Grades 5-8) series.* www.nasa.gov. The site has been viewed April 2020.

[19] Clark, Stephen (18 April 2016). "Attitude control failures led to break-up of Japanese astronomy satellite". Spaceflight Now. Retrieved 21 April 2016.

[20] "Supplemental Handout on the Operation Plan of the X-ray Astronomy Satellite ASTRO-H (Hitomi)" (PDF). JAXA. 28 April 2016. Retrieved 13 June 2016.