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# Fault Tolerant Control for Robot Manipulator

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# Fault Tolerant Control for Robot Manipulator

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**ABSTRACT**

With the continuous increase in complexity and costs of industrial systems, there is less tolerance for performance degradation, productivity decrease and safety hazards. Therefore, early detection and identification of potential abnormalities and faults in such systems are crucial to ensure they operate in optimal conditions. The work presented in this thesis intends to develop and improve observer-based fault detection and isolation techniques for robot manipulator. Furthermore, the goal is to generate robust methods for fault detection and isolation that can improve the decision process regarding fault isolation and identification. Moreover, this work proposes a fault-tolerant control method to improve the safety and reliability of control systems against fault and failures. The control system that can automatically compensate the fault effect in the system components, while keeping the system stability along the desired level of the global performance.
**Keywords : Fault detection and isolation, sensor fault, actuator fault, residuals, high gain observer, sliding mode observer, robot manipulator.**

**RÉSUMÉ**

Avec l'augmentation continue de la complexité et des coûts des systèmes industriels, il y a moins de tolérance à la dégradation des performances, à la diminution de la productivité et aux risques pour la sécurité, ce qui nécessite grandement de détecter et d'identifier tout type d'anomalies et de défauts potentiels le plus tôt possible pour minimiser la dégradation des performances et éviter les situations dangereuses pour le robot manipulateur. Dans ce contexte, l'objectif de cette thèse est de développer et d'améliorer la détection et l'isolation des défauts, au niveau des capteurs et des actionneurs dans un robot manipulateur, à base des observateurs ainsi de générer des méthodes robustes pour la détection et l'isolation de défauts afin d'améliorer l'étape d'isolation et d'identification des défauts. De plus, ce travail propose une méthode de commande tolérante aux défauts pour améliorer la sécurité et la fiabilité des systèmes de contrôle contre les défauts. Un système de contrôle qui peut automatiquement compenser un effet de défaut dans les composants du système tout en maintenant la stabilité du système avec le niveau souhaité de performance globale.


Mots clés: détection et isolation des défauts, défaut de capteur, défaut d'actionneur, résidus, observateur à grand gain , contrôleur, observateur en mode glissant, robot manipulateur.

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## LIST OF ABBREVIATIONS

| | |
|---|---|
| ANAT | Articulated Nimble Adaptable Trunk |
| FTC | Fault tolerant control |
| FDI | Fault detection and isolation |
| MIMO | Multi Input Multi Output system, multi input multi output system |

# NOTATION

| | |
|---|---|
| $d_i$ | Distance between the two marks $i$ and $i+1$, $m$ |
| ${}^i_jT$ | Homogeneous transformation matrix from the reference $i$ to the reference $j$ |
| ${}^i_jR$ | Rotation matrix from reference $i$ to reference $j$ |
| $K$ | Kinetic energy, $Joule$ |
| $U$ | Potential energy, $Joule$ |
| $W$ | Work, $Joule$ |
| $\tau_i$ | Torque applied to joint $i$, N.m |
| $m_i$ | Represents the mass of the body $i$, Kg |
| ${}^j_ci\nu$ | Linear velocity of the body $i$ expressed in the reference $j$, m/s |
| ${}^j_ci_W$ | Angular velocity of body $i$ expressed in the frame $j$, $m/s^2$ |
| $Q_nc$ | Matrix of non-conservative forces, $N$ |
| $I_i$ | The tensor of the inertias of the body $i$ |
| $g$ | Gravitational acceleration, $m/s^2$ |
| $c_i$ | Body center of mass $i$ |
| $M$ | Robot mass matrix |
| $F$ | Vector of centrifugal, Coriolis, friction and gravity forces |
| ${}^i_jj$ | Jacobian matrix from reference $i$ to reference $j$ |
| $\dot{x}$ | The velocity vector, $m/s^2$ |
| ${}^i_jJ^+$ | Generalized inverse of the reference $i$ to the reference $j$ |
| $N$ | Null space of 0 $J$ 7 |
| $K_p$ | Proportional gain of the controller |
| $K_d$ | Derivative gain of the controller |
| $S$ | Sliding function |
| $sign(S)$ | Signum function of the sliding function $S$ |
| $q$ | Robot $q_i$ column vector |

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# INTRODUCTION

Nowadays, manufacturing industries have three factors that make it possible to maintain competitiveness which are: cost, productivity and agility of the means of production, in particular in order to respond for the demands of the "Mass-Customization" phenomenon. For an increasing number of industrial applications, robots are used to meet these requirements. They represent a sophisticated means of production on the premise that these manipulators are more agile, more flexible, and less expensive than specialized machine tools. Although, machine tools are structurally more rigid and poly-articulated robots generally have more workspace. There is an increasing demand for harnessing these advantages for positioning, pick-and-place tasks as well as continuous character operations such as machining. These new robotic processes require increased precision during their implementation in order to be able to guarantee the quality of the production [1, 2]. Improving the precision of industrial robots remains a subject facing many technological obstacles.

For this thesis, we have chosen a hyper redundant modular robot, i.e. a robot that has internal movement. This internal movement does not influence the trajectory of the effector. It thus allows the robot to perform an auxiliary task such as: Avoiding obstacles, optimizing the robot's energy expenditure, even accessing a difficult environment.

The robot we are controlling uses the Articulated Nimble Adaptable Trunk technology, known as ANAT [3]. This technology makes it possible to avoid obstacles and also offers great reliability. Finally, its most interesting aspect is its modularity, the robot is designed in such a way that we can vary the number of joints of the robot.

Modular and reconfigurable robots are characterised by interchangeable links and joint modules of various sizes. Using standard mechanical and electrical interfaces, the recombination of modules is carried out to create nemerous robot configurations that meet a wide range of different task requirements.

Such a modular and reconfigurable robot system has several advantages over conventional manipulators:

• Cost effectiveness: lowers manufacturing cost and ease of replacement brings about a reduction in cost;

• Modularity: introduces flexibility to robots by making them reconfigurable;

• Manufacturability: reduces the number of operations for an individual part and thus simplifies manufacturing; making them easier and cheaper to build;

• Redundancy: implies highly redundant systems since many modules are available due to the ease of manufacture. Thus, enhances diagnosability;

• Repairability: if a module fails, it is easy to replace the module since there are others that can take up the same job;

• Durability: against system malfunctions due to replaceable standardized units.

"Can a modular control technique be designed for any modular and reconfigurable robot?" is the main question posed. Is the modularity achieved in the mechanical design achievable in the control design too? Can the control law be made independent of each new configuration of the robot? Can faults at each joint module be detected and tolerated with minimum or no information from the other modules?

**Motivation and Objectives of Research:**

Our motivation is fault detection and isolation and fault tolerant control for robot manipulator. Several types of fault diagnosis and fault-tolerant control algorithms have been developed for robot manipulators. These methods are divided into four main classes: Signal-based, model-reference, knowledge-based, and hybrid techniques [4, 5]. All methods for fault diagnosis have specific advantages and challenges. Signal-based fault diagnosis extracts the main features from output signals, and because of the presence of disturbances, the performance of this method is degraded. Knowledge-based fault diagnosis is highly dependent on the historical data used for training, which incurs high computational costs for real-time data. The model-reference method identifies faults using a small dataset, but it requires an accurate system model [6]. Hybrid fault detection, estimation, and identification techniques use a combination of high-performance methods to design a stable and reliable technology [7].

Diverse observer-based techniques have been adopted for fault detection, estimation, and identification. Generally, they can be classified into two main groups: Linear-based observers and nonlinear-based observers [8].

Proportional integral (PI) observers are linear. They have been used in different systems for fault diagnosis. Still, they are ineffective in the presence of uncertainties and disturbances [9]. Nonlinear observers (e.g., adaptive, sliding mode, feedback linearization, and fuzzy) were introduced to compensate for the limitations of linear observers [8, 10, 11]. Feedback linearization observers are stable; however, they are not adequately robust [12]. Sliding mode observers are robust and stable, but chattering is the main drawback of this technique for fault diagnosis in the presence of uncertainties [8]. The fuzzy logic observer has an acceptable state estimation and works in uncertain conditions. However, reliability is the main drawback of this technique [11]. Among the available options, hybrid methods provide the most suitable techniques for fault detection, evaluation, and identification in a robot manipulator.

Linear and nonlinear fault-tolerant control algorithms are the main techniques to reduce or eliminate the effects of faults in robot manipulators. Coupling effects and increased gear ratio are the main drawbacks of linear fault-tolerant control algorithms [13]. Model-reference fault-tolerant algorithms, knowledge-based techniques, and hybrid fault-tolerant control methods are the main techniques used in robot manipulators [13, 14]. Model-based and knowledge-based fault-tolerant control algorithms have several advantages, such as system knowledge, stability, robustness, and reliability. Still, they face a significant challenge in the unlimited level of a faulty signal [14]. Hybrid fault-tolerant algorithms are used to address that issue [15, 16]. The sliding mode technique can be an excellent candidate for a robust fault-tolerant control algorithm, but it must address the challenge of chattering. Various techniques have been proposed to attenuate chattering [13, 16]. The higher-order sliding mode technique for fault-tolerant control algorithm is suitable for reducing chattering and the effects of faults in robot manipulator.

**Contributions:**

The objective of this thesis is to provide modern fault detection and isolation algorithms for automated systems that are of concern to most manufacturers in order to provide added value for high performance processes with greater reliability and robustness. Thus, the work developed in this thesis aims to provide solutions to these industrial issues relating to the development of fault detection and isolation strategies in the case of sensor and actuator fault. Therefore, the other objective of this thesis is to synthesize a fault tolerant control law. The resulting fault tolerant systems allow to increase the safety and availability of production tools. The main contribution of our work is to generate fault tolerant systems by synthesizing both diagnostic modules as well as a reconfiguration mechanism upon loss of sensors taking into consideration the information from the diagnostic module. This global view of the problem of automation for the implementation of fault tolerant systems has led us to study both faut detection and isolation methods and fault tolerant control methods. The principal idea of our work are:

• Develop fault detection and isolation algorithms for a robot manipulator.

• Present techniques for fault-tolerant control for a robot manipulator.

• Propose method for fault tolerant control.

**Outline of Thesis:**

This thesis is organized into four chapters outlined as follows:

Chapter (1) introduces state of the art concerning the geometrical, kinematic, and dynamic modelling of poly-articulated serial structures and the model of the robot manipulator, more precisely the model used in our thesis.

Chapter (2) focuses on fault detection and isolation for robot manipulators. We present different types of faults and fault detection and isolation methods, their objectives and their various classifications. Furthermore, the advantages and disadvantages of each method are highlighted.

Chapter (3) describes the application and results for fault detection and isolation with the proposed algorithms for the sensors and actuators faults. These techniques present a high level of precision and simple implementation.

Chapter (4) provides a fault-tolerant control technique for robot manipulator and their simulation results given by the exposed methods. The results show the effectiveness and robustness of fault detection and isolation and fault tolerant control.

The results obtained in this thesis have given rise to the following publications:

**International journals with peer review:**

• Omali, K.O., Kabbaj, M.N., Benbrahim, M., Fault Diagnosis and Fault-Tolerant Control with High-Order Sliding Mode for Robot Manipulator, International Journal of Power Electronics and Drive Systems (IJPEDS), Vol 12, No 3: September 2021, accepted.

• Omali, K.O., Kabbaj, M.N., Benbrahim, M., Fault detection and isolation using sliding mode observers with sensor fault in robot manipulator, International Journal of Digital Signals and Smart Systems 5(2):182, January 2021.
DOI: 10.1504/IJDSSS.2021.114560.

• Omali, K.O., Kabbaj, M.N., Benbrahim, M., Actuator fault detection and isolation for robot manipulator using higher order sliding mode observers, Indonesian Journal of Electrical Engineering and Computer Science, 2020, 17(3), pp. 1150-1156.
DOI: 10.11591/ijeecs.v17i3.pp1150-1156.

**Chapter in book:**

• Omali, K.O., Kabbaj, M.N., Benbrahim, M., Nonlinear Observer-based fault detection and isolation for a manipulator robot, Studies in Systems, Decision and Control Volume 175, Pages 163-185, 2019.
DOI: 10.1007/978-981-13-2212-9-7.

**International conferences with proceedings and reading committee:**

• Omali, K.O., Kabbaj, M.N., Benbrahim, M., Observer-Based to Fault Detection and Isolation for Robot Manipulator, Conference: International Meeting on Advanced Technologies in Energy and Electrical Engineering, January 2020.
DOI: 10.5339/qproc.2019.imat3e2018.17.

• Omali, K.O., Kabbaj, M.N., Benbrahim, M., Fault Detection and Isolation for Manipulator Robot, International Symposium on Advanced Electrical and Communication Technologies, ISAECT 2018, Proceedings18 January 2019, International Symposium

on Advanced Electrical and Communication Technologies, ISAECT 2018, 23 November 2018.
DOI: 10.1109/ISAECT.2018.8618764.

• Omali, K.O., Kabbaj, M.N., Benbrahim, M., Sensor fault detection and isolation for robot manipulator, AIP Conference Proceedings Volume 207420, February 2019, 2nd International Conference on Applied Mathematics, ICAM 2018, 26 October 2018-27 October 2018.
DOI: 10.1063/1.5090640.

• Omali, K.O., Kabbaj, M.N., Benbrahim, M., Sensor Fault Detection and Isolation for a Robot Manipulator Based on High-Gain Observers, Advances in Intelligent Systems and Computing, 2019, 756, pp. 426–435. 2nd International Conference on Real-Time Intelligent Systems, RTIS 2017, 18 October 2017-20 October 2017.
DOI: 10.1007/978-3-319-91337-7-38.

# CHAPTER 1

# MODELING OF POLYARTICULATED ROBOTS

This chapter expose to present the various models cited and applied to an open serial structure. The robot we are controlling uses the Articulated Nimble Adaptable Trunk technology known as ANAT. This technology makes it possible to avoid obstacles and also offers great reliability. Finally, its most interesting aspect is its modularity. Indeed the robot is designed so that we can vary the number of joints of the robot. These models are adapted to the ANAT robot in which our tests are doing, for which a parameterization method according to the Denavit-Hartenberg parameters ($DH$) convention is proposed. We propose to present an appropriate modeling approach where rigid and flexible dynamics are taken into account. Before tackling this approach, we will introduce a few definitions to clarify the notion of precision.

## 1.1 Generalities

The term robot was introduced in 1920 by the Czech novelist Capek, means an android machine capable of replacing humans at work. Today, robotics affects different fields of research such as: artificial life to make more autonomous robots and allow them to continue their operation without human intervention; collective intelligence, where robots interact with each other; nanotechnologies to design micro-robots, usable inside the human body for example. As we can see, the uses are varied and practically limitless. But let's go back for a moment to a definition of the term robot: "Designed to perform certain tasks in place of humans (intervening in a production line industrial, moving on Mars or in dangerous places ...), robots are more than just computers: they must be able to perceive what surrounds them and react accordingly ". For this project, a hyper redundant modular robot is considered, i.e. a robot that has internal movement. This internal movement does not influence the trajectory of the effector. It thus allows the robot to perform an auxiliary task such as: avoiding obstacles, optimizing the energy

expenditure of the robot or even access a difficult environment.
A review of the main advantages and disadvantages of serial robots are shown in table (1.1).

Table 1.1 – Main advantages and disadvantages of robots with serial architectures

| Advantages | Disadvantages |
|---|---|
| - Very large workspace | - Transportable mass / robot mass ratio very low compared to that of parallel robots |
| - Great flexibility and great ease of positioning thanks to their architecture. | - Poor precision due to accumulated errors at each joint.<br><br>-Ease of propagation and amplification of errors precision and vibration to the terminal organ. |
| - Easy to model structure requiring less complex control when compared to parallel robots. | - Limited dynamic behavior because of<br><br>the large masses and inertias of the constituent bodies. |

The process of modeling a robot requires an adequate method for describing their morphology. It can be noted that:
- Geometric models and kinematic models express the position and speed of the terminal organ as a function of the articular variables of the mechanism and vice versa;
- Dynamic models defining the equations of motion of the robot, which make it possible to establish the relationships between torques $\setminus$ forces exerted by the actuators and the positions, speeds and accelerations of the joints.

## 1.2 Precision: concepts and definitions

In this part we introduce some definitions commonly used in the performance analysis relating to the positioning capabilities of a manipulator robot. The performance criteria as well as the corresponding test methods for industrial robots are provided by the $ISO9283$ standard $[ISO, 1998]$. This standard gives definitions of repeatability and installation accuracy. It is always useful when trying to identify the different causes of position and orientation errors of a robot's terminal organ. However, it must be combined with other complementary definitions taken from metrological standards.

### 1.2.1 Precision or repeatability

Fidelity is defined as the ability to give, for the same measurement, similar values [17]. There are two levels of precision in metrology: repeatability and reproducibility. The difference between these two terms lies in the experimental conditions.
In the context of repeatability, the results are obtained by the same method, on identical tests, in the same laboratory, by the same operator using the same equipment and during a well-determined time interval. Within the framework of reproducibility, the results are obtained by the same method, on identical tests, in different laboratories, with different operators using different equipment. In the following, we are particularly interested in repeatability. For a robot, repeatability characterizes the dispersion of the poses reached by the robot when it is commanded to achieve the same several times point. It is very difficult to interfere with the loyalty of a robot. Indeed, the causes of poor fidelity arise from random phenomena such as play, friction, wear at links. It is possible to take care of the realization of the links, however it is impossible to eliminate all the phenomena which penalize repeatability. Added to this is the precision that is defined as the robot's ability to move precisely to a desired position in $3D$ space. The precision and repeatability pair therefore describes the ability of a robot to reach a desired set point with the minimum of variance figure (1.1).

### 1.2.2 Trueness and accuracy

Trueness or measurement bias refers to the closeness of agreement between the average value obtained from a large series of test results and an accepted reference value. However, it should not be confused with accuracy. The latter designates a single measured value compared to a given reference value. Therefore, the measurement of accu-

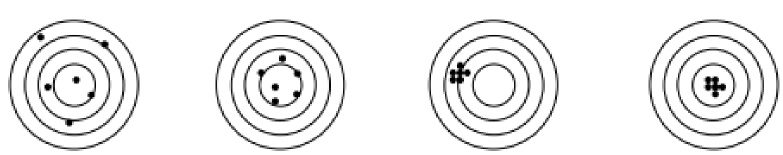


Figure 1.1 – Repeatability and static precision

racy is only the robot pose error or in other words, the measurement of accuracy static robot as indicated in the standard cited above. The installation accuracy error of industrial robots is a few millimeters. The origin of this error is manifested by several structural and geometric factors. As for structural factors, we can distinguish faults due to the load transported, friction problems, mechanical games, thermal drifts and the positioning of each arm in relation to the others. Regarding geometric faults, they are often associated with axis offset faults accompanied by poor parameterization of the geometric model and the definition of the component frame terminal in space. To this is added the dynamic precision or the problem of following the trajectory figure (1.2).

This precision is affected by the same sources cited above to which are added inertia, control parameters and joint elasticity problems that cause vibratory behavior. Indeed, along its programmed trajectory, the effector undergoes a deviation while remaining in a zone of uncertainty called dynamic uncertainty. This uncertainty depends mainly on:

- Transmission defects of each joint and flexibility of the arms,
- The architecture of the manipulator.

Several methods have been developed to remedy this imprecision problem and make it possible to correct the main faults of serial robots. The most popular solutions in the industry are the calibration of the robot. Calibration is the solution that improves the static accuracy of robot positioning without any modification to the mechanical structure or the design of the robot itself.

In general, the calibration makes it possible to update the nominal values of the geometric parameters given by the manufacturer in the control. This operation requires obviously an external measurement system. This is usually a $3D$ measuring system such as a laser tracker or a photogrammetric system [18]. Once the measurements have been made, the operation then consists of determining the difference between a given geometric model and experimental data on the robot in order to optimize the relative parameters. This operation improves the static precision of manipulators by approximately 97% [19]. Another solution is to install additional encoders at the axis end of the robot to measure faults in the transmission chain. The encoder feedback will be systematically injected into the upstream control loop [20]. This type of solution increases the price

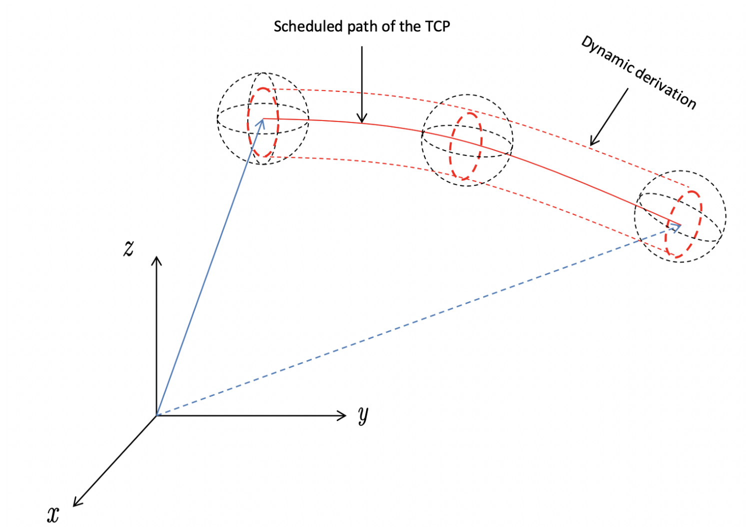



Figure 1.2 – Definition of dynamic error

of the robot and poses new technological problems, in particular stability problems. A third approach is based on the development of a behavioral model making it possible to generate an adapted command and making it possible to compensate a large part of the tracking errors in dynamics. In the rest of this chapter, we suggest to develop an elastodynamic modeling of an industrial manipulator.

## 1.3 Geometric Modeling of Manipulator Robot

### 1.3.1 Definition of the terminal organ situation

Defining the situation of the robot's terminal organ requires knowledge of its position and orientation, usually known as the robot pose. The number of parameters required for the complete definition of the pose of a rigid body in space is six: three for position and three for orientation. As for the definition of the position, we adopt cartesian coordinates which are the easiest to use. Other representations also exist such as cylindrical and spherical coordinates. Regarding the definition of the orientation of the terminal organ, several conventions are presented in the literature [21]:
Euler angles; angle plus vector; quaternion; rotation matrix or guiding cosines.

The minimum representation of orientation is defined by three parameters such as Euler angles. The most common non-minimal representation is the nine rotation matrix components. The quaternion or angle plus vector representation are representations with four components, one more than the Euler angles. The advantages of the use of quaternions are widely discussed in [22], while [23] proposes kinematic modeling and a control strategy based on unit quaternions of a patella wrist of a manipulator robot. A comparison between the different formalisms is proposed in [24]. In what follows, we introduce the classical methods of parameterization for serial structures.

### 1.3.2 The geometrical parameters

In the literature, there are several conventions for defining the position as well as the relative orientation of successive landmarks. The most widely used technique to model a manipulator robot consists of using the $(DH)$ parameters, valid for simple open structures [25]. This convention uses four parameters for the relative location of two successive landmarks: two angles and two distances. Let us consider a serial manipulator arm with a simple open architecture made up of $n$ mobile bodies supposed to be perfectly rigid and whose joints are rotoid. Let the axis $i$ be the joint which connects the arm $i-1$ and the arm $i$ as shown in figure (1.3)[27]. We associate with the $i-th$ moving body a Cartesian orthonormal basis $R_i-1$, with $i = 1,2,....,n$. The positioning of a joint according to the $DH$ convention is carried out by the minimum necessary number of four parameters for a rotoid figure (1.3):

- The $z_i$ axis is carried by the axis of rotation of the $i+1$ joint;
- The $x_i$ axis is carried by the perpendicular common to the $z_i$ and $z_i+1$ axes;
- The $y_i$ axis will complete the right hand rule in order to define a direct orthonormal coordinate system;
- The origin $O_i$ is the intersection of the $z_i$ axis and the normal common to the $z_i-1$ and $z_i$ axes;
- Let the point $O_i^{'}$ the intersection of the $z_i-1$ axis and the normal common to the $z_i-1$ and $z_i$ axes.

This allows us to facilitate notations and definitions later.

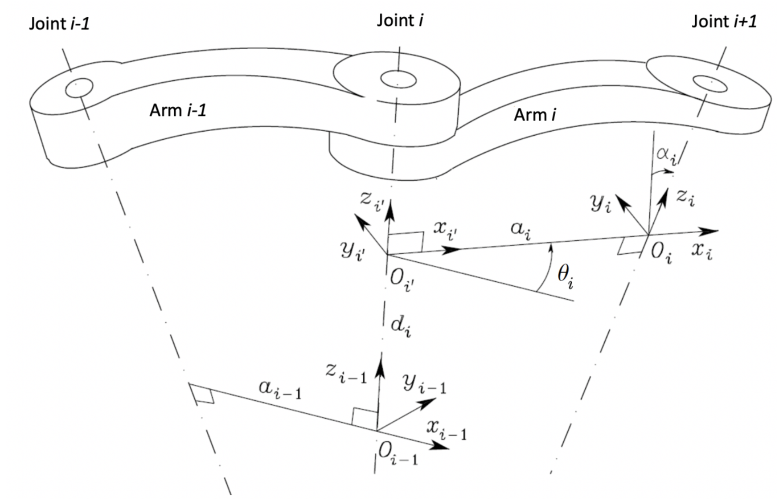



Figure 1.3 – The geometric parameters of Denavit Hartenberg

The definition of the reference marks being established, the position and the orientation of the base $R_i$ with respect to $R_i{-}1$ is expressed as a function of the following four parameters:

- $\theta_i$ is the angle of rotation between $\vec{x}_i{-}1$ and $\vec{x}_i$ around $\vec{z}_i{-}1$;

- $\alpha_i$ is the offset angle between the $\vec{z}_i{-}1$ and $\vec{z}_i$ axes around $\vec{x}_i$ always using the right hand rule. It defines among other things the torsion of the arm or the warping;

- $\alpha_i$ represents the length of the arm, it is the distance between $O_i^{'}$ and $O_i$ along $\vec{x}_i$;

- $d_i$ is the distance between $O_i - 1$ and $O_i^{'}$ according to $\vec{z}_i{-}1$.

The *DH* convention remains general and does not give a single definition of the reference in the following cases:

- When two consecutive axes are parallel, the common perpendicular of distance $d_i$ according to the associated frame of reference is not properly defined;

- For a coordinate system $R_i$, only the direction of $z_i$ is fixed. However, the point of origin $O_i$ as well as the direction vector $\vec{x}_i$ are arbitrarily chosen.

## 1.4 Dynamic Model of Manipulator Robot

The dynamic model of a manipulator robot is given by the set of mathematical relationships between the couples (forces) applied to the actuators and the temporal evolution of joint positions, speeds and accelerations [28]. Various definitions are adopted to describe the dynamics of multi-body systems; [26]. There are two types of dynamic models:
- The direct dynamic model which expresses the joint accelerations as a function of the positions, speeds and torques of the joints;
- The inverse dynamic model, or quite simply dynamic model, which expresses the couples according to the articular variables.
In general, the dynamic model is used for simulation, synthesis of controllers and mechanical design of transmission elements. Some control algorithms require that the inverse dynamics problem to be solved. This means that the engine torque is calculated from the desired displacements and its successive derivatives. However, for the simulation, the differential equations of the model must be solved knowing that the input of the system matches the torque supplied by the actuators [27].

## 1.5 Modeling the ANAT robot

Any command or control of a robot goes through its modeling. This modeling includes different phases. first the determination of the physical characteristics of the robot. Then the determination of the kinematics of the robot after having calculated the homogeneous transformation matrices. Finally, the dynamic modeling.
Kinematics and differential kinematics allow us to translate a trajectory expressed in the workspace, into a trajectory expressed in the space of the joints. By trajectory we mean the position, speed and acceleration desired to perform a certain task. Thus, we will be able, to achieve a triangle, for example, to determine for each joint the position, speed and the acceleration to follow. We will see in this chapter only the kinematics, since we need to deal with the differential kinematics to achieve obstacle avoidance by using the robot redundancy.

Dynamic modeling allows to associate with this desired trajectory in the joint space, a torque to be applied to the motors to effect the displacement. Several methods are available. The Lagrange method, Newton Euler Method or the connecting graphs method. We have chosen Lagrange method because we are familiar with it.

### 1.5.1 The ANAT robot description

Articulated Nimble Adaptable Trunk technology is a new innovation in robotic architecture that allows the creation of highly robust and intelligent robots with reconfigurable modular architectures. This technology was invented by the founder of Robotics Design Inc., Mr. Charles Khaïrallah [3]. In use in over seven ground-breaking products worldwide, ANAT technology represents robotic architecture of the future.

ANAT was exclusively designed and patented by Robotics Design (patent 6,323,615B1) [3]. ANAT has many properties that give it flexibility and dexterity in larger movements than most existing manipulators. This asset comes mainly from the robot's redundant modular trunk, which enables it to perform auxiliary obstacle avoidance tasks and therefore allows it to work in more complex and difficult-to-access workspaces. In addition, the robot's redundancy ensures the main task continues even in the case where one or more motors of the trunk are defective. Thus, it is possible to implement on ANAT avoidance tasks of obstacle in the cartesian space provided that they have the necessary resources for the realization.

The invention consists of a series of motorized $U$ and $H$ shaped modules that function much like cells of the human body; they work together to achieve a common goal. These modules connect to each other along four points, allowing them to evenly distribute pressure amongst themselves like the simple yet timeless design of the Roman arches. This allows ANAT robots to carry exceptionally heavy payloads, and withstand pressure applied on any point of their modules. ANAT modules can be configured into a diverse spectrum of robot configurations such as fixed manipulators, mobile robots, flexible ergonomic arms (DOF) degree of freedom (up to 32 D.O.F.), and much more. Motors are contained in the central axis of each module, so regardless of the quantity or impact point of outside pressure placed on the module, no strain is placed on the motor. These modules have one degree of freedom each, bend and fold relatively to each other along their axis, are highly flexible and able to avoid obstacles with ease. Modules can be connected in a myriad of configurations like Lego blocks, and can be reconfigured from their initial form to form another robot. This allows the same modular technology used in the design of an arc-welder or pick-and-place manipulator to be re-used in forming a mobile robot such as an unmanned mining vessel or vehicle. A robot using this simple and innovative architecture which performs a single specialized application can be formed by modules varying only in size, or a single robot can be formed to specialize in several applications, with the only variable being attached accessories. This also drastically simplifies and reduces costs for maintenance, as a faulty module can be easily replaced with an identical one. In short, nimble, adaptable and durable modular robots are now possible through this technology and new products are born into the ANAT robot family daily [264].

Figure 1.4 – ANAT robot [264]

Figure (1.4) below shows the schematic representation of the robot. It has seven degrees of freedom composed as follows: Prismatic joint, a part redundant system consisting of three parallel rotary joints and an effective effector to orient the tool in a desired position and consisting of three rotary joints whose axes of rotation are perpendicular to one another.

We say redundancy when the number of degrees of freedom of the manipulator is greater than the number of degrees of freedom of the task to be performed. When there is redundancy, there is an infinity of possible positions for a fixed placement of the tool. Thus some members of the manipulator may be in motion it's call it the internal movement of the robot. Redundancy allows to optimize the performance of a robot and to avoid constraints imposed by the articular limits or the obstacles.

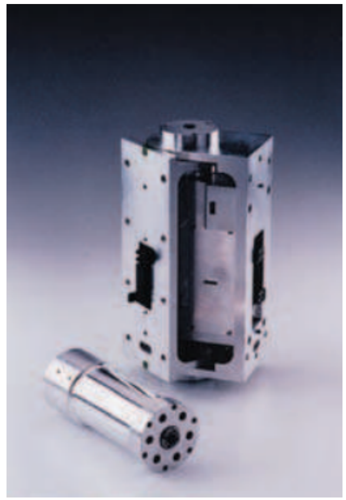


Figure 1.5 – One of the robot modules

An interesting property of ANAT lies in its modularity which facilitates its maintenance and performs "Plug and Play" tasks. Figure (1.5) shows one of the ANAT modules. Moreover, the mechanical structure of the robot also has interesting advantages over conventional manipulators. First the aluminum structure of ANAT makes it relatively light. Second, the load distribution on the robot motors is optimized, in contrast to the usual manipulators on which the stresses are unequally distributed. In addition, for common manipulators, motors may be oversized to accomplish the same task.
The industrial applications of such a robot are multiple. ANAT can be particularly used in the paint and finishing industries, the automotive industries, as well as the aeronautical and naval industries.

### 1.5.2 Robot workspace

The robot is subjected to some mechanical displacement stresses $q_m$ shown in table (1.2).

### 1.5.3 Robot redundancy

As defined in the previous chapter, we speak of redundancy when the number of freedom degrees of the manipulator is greater than the number of freedom degrees of

Table 1.2 – Robot workspace

| *Articulation* | *Type* | *Space* |
|---|---|---|
| 1 | Prismatic | of $L_0$=0.57m at 1.27m |
| 2 | Rotary | of $-90^\circ$ $+90^\circ$ |
| 3 | Rotary | of $-90^\circ$ $+90^\circ$ |
| 4 | Rotary | of $-90^\circ$ $+90^\circ$ |
| 5 | Rotary | of $-90^\circ$ $+90^\circ$ |
| 6 | Rotary | of $-90^\circ$ $+90^\circ$ |
| 7 | Rotary | of $-n\pi$ at $n\pi$ |

the task to perform. In the case of the ANAT robot, the parallel rotary joints placed between the prismatic joint and the effector, make up the redundant part. This part is modular, that is to say that you can add or remove rotary joints. We will see later, and in particular when we will realize the inverse differential kinematics, how we will use the robot redundancy for this project.

## 1.6 Direct and inverse kinematics

This part will make it possible to translate the position of the robot from the workspace to that of the joints. We will first assign the benchmarks necessary for the calculation homogeneous transformation matrices that make it possible to determine the kinematics of the robot.

### 1.6.1 Assignment of benchmarks

A systematic method of attribution of the reference marks must be applied if one wishes to obtain the parameters of craig allowing to determine the matrices of homogeneous transformations [30]. This method is illustrated in figure (1.6). In this figure, the axis $z$ of the various reference marks are aligned with their respective articulations. In addition, the axis $x$ is chosen so as to be perpendicular to the axis $z$ of the frame to which it belongs and to the axis $z$ of the following frame. Finally the axis $y$ is determined by respecting the rule of the right hand.

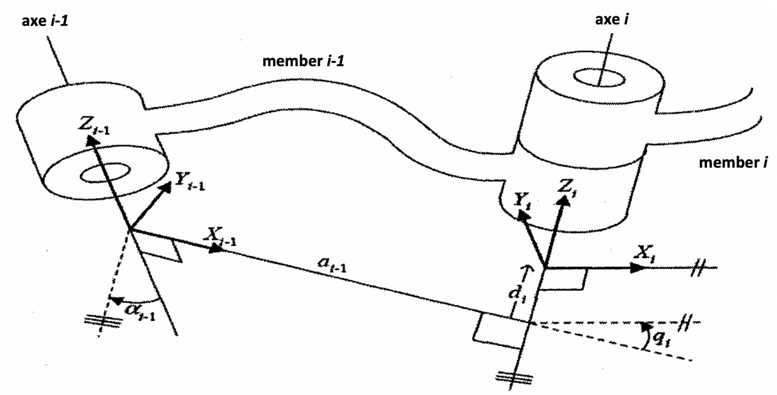



Figure 1.6 – Schematization of the craig parameters from member $i-1$ to member $i$

In the case of our robot, we set the benchmarks using this method. Figure (1.7) shows the chosen axis systems [31].

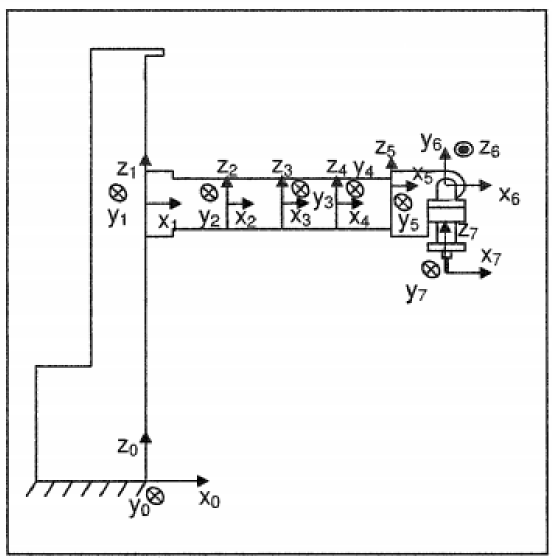


Figure 1.7 – Representation of the seven axes of ANAT

### 1.6.2 Matrices of homogeneous transformations

The homogeneous transformation from one member to the previous one can be fully characterized by four parameters called *DH* parameters. They allow to systematically obtain the transformation matrix from one member to another. These parameters are assigned according to craig's convention and illustrated by figure (1.6). These parameters are defined as follows:

- The parameter $a_{i-1}$ is a translation between the reference $i-1$ and the reference $i$ along the axis $X_{i-1}$

- The parameter $\alpha_{i-1}$ is a rotation around the axis $X_{i-1}$ which makes it possible to make the axis $Z_{i-1}$ parallel to the axis $Z_i$.

- The parameter $d_i$ is a translation between the intersection of the extensions of the axes $X_{i-1}$ and $Z_i$ and the reference $i$.

- The parameter $q_i$ is a rotation around the axis $Z_i$ which makes it possible to make the axis $X_{i-1}$ parallel to the axis $X_i$.

Table 1.3 – Denavit-Hartenberg parameters of ANAT

| $Articulation$ | $\alpha_{i-1}$ | $a_{i-1}$ | $d_i$ | $q_i$ |
|---|---|---|---|---|
| 1 | 0 | 0 | $q_1$ | 0 |
| 2 | 0 | $L_1$ | 0 | $q_2$ |
| 3 | 0 | $L$ | 0 | $q_3$ |
| 4 | 0 | $L$ | 0 | $q_4$ |
| 5 | 0 | $L$ | $L_2$ | $q_5$ |
| 6 | $\pi/2$ | $L_3$ | 0 | $q_6$ |
| 7 | $-\pi/2$ | 0 | $-L_4$ | $q_7$ |

- $L = L_1 + L_2 + L_3 + L_4$

According to figure (1.6), the homogeneous transformation matrix from reference $i$ to reference $i-1$ is given by the following relation:

$$ {}^{i-1}_{i}T = \begin{bmatrix} cq_i & -sq_i & 0 & \alpha_{i-1} \\ sq_i c\alpha_{i-1} & cq_i c\alpha_{i-1} & -s\alpha_{i-1} & -s\alpha_{i-1}d_i \\ sq_i s\alpha_{i-1} & cq_i s\alpha_{i-1} & c\alpha_{i-1} & c\alpha_{i-1}d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1.1} $$

Where: $cq_i = \cos(q_i)$ and $sq_i = \sin(q_i)$

We calculated the passage matrices using Maple calculation software and a library designed for this purpose by [32].

Here is the transition matrix from the base frame 0 to the last frame of reference 7 which will allow us to determine the kinematics of the robot:

$$ {}^{0}_{7}T = \begin{bmatrix} {}^{0}_{7}T_{11} & {}^{0}_{7}T_{12} & {}^{0}_{7}T_{13} & {}^{0}_{7}T_{14} \\ {}^{0}_{7}T_{21} & {}^{0}_{7}T_{22} & {}^{0}_{7}T_{23} & {}^{0}_{7}T_{24} \\ {}^{0}_{7}T_{31} & {}^{0}_{7}T_{32} & {}^{0}_{7}T_{33} & {}^{0}_{7}T_{34} \\ {}^{0}_{7}T_{41} & {}^{0}_{7}T_{42} & {}^{0}_{7}T_{43} & {}^{0}_{7}T_{44} \end{bmatrix} \tag{1.2} $$

$$ \begin{cases} {}^{0}_{7}T_{11} = [c_{234567} + c_{23457-6} + c_{23456-7} + c_{2345-6-7}] + \frac{1}{2}[-c_{2345-7} + c_{23457}] \\ {}^{0}_{7}T_{12} = \frac{1}{4}[-s_{234567} - s_{23457-6} + s_{23456-7} + s_{2345-6-7}] - \frac{1}{2}[s_{23457} + s_{2345-7}] \\ {}^{0}_{7}T_{13} = \frac{1}{2}[-s_{23456} + s_{2345-6}] \\ {}^{0}_{7}T_{14} = \frac{1}{2}L_4[s_{23456} - s_{2345-6}] + L_3 c_{2345} + L[C_{234} + C_{23} + C_2] + L_1 \\ {}^{0}_{7}T_{21} = \frac{1}{4}[s_{234567} + s_{23457-6} + s_{23456-7} + s_{2345-6-7}] + \frac{1}{2}[-s_{2345-7} + s_{23457}] \\ {}^{0}_{7}T_{22} = \frac{1}{4}[c_{234567} + c_{23457-6} - c_{23456-7} - c_{2345-6-7}] + \frac{1}{2}[c_{23457} + C_{2345-7}] \\ {}^{0}_{7}T_{23} = \frac{1}{2}[c_{23456} - c_{2345-6}] \\ {}^{0}_{7}T_{24} = \frac{1}{2}L_4[-c_{23456} + c_{2345-6}] + L_3 s_{2345} + L[s_{234} + s_{23} + s_{82}] \\ {}^{0}_{7}T_{31} = \frac{1}{2}[s_{67} + s_{6-7}] \\ {}^{0}_{7}T_{32} = \frac{1}{2}[c_{67} + c_{6-7}] \\ {}^{0}_{7}T_{33} = c_{66} \\ {}^{0}_{7}T_{34} = -L_4 c_6 + L_2 + q_l \\ {}^{0}_{7}T_{41} = 0 \\ {}^{0}_{7}T_{42} = 0 \\ {}^{0}_{7}T_{43} = 0 \\ {}^{0}_{7}T_{44} = 1 \end{cases} \tag{1.3} $$

where $c_i = cos(q_i)$, $c_{ij} = cos(q_i + q_j)$, $si = sin(q_i)$, $si - j = sin(q_i - q_j)$, $c_{ij-h} = cos(q_i + q_j) - cos(q_h) = sin(q_i)$ and $s_{ij} = sin(q_i + q_j)$.

### 1.6.3 Expression of direct and inverse kinematics

TDue to the homogeneous transformation matrix ${}^0_7T$, we obtain the position of the effector in the reference frame of the base:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} L_4 c_{2345} s_6 + L_3 c_{2345} + L[c_{234} + c_{23} + c_2] + L_1 \\ L_4 s_{2345} s_6 + L_3 s_{2345} + L[s_{234} + s_{23} + s_2] \\ -L_4 c_6 + L_2 + q_1 \end{bmatrix} \tag{1.4}$$

Moreover, by identifying the rotation matrix ${}^0_7R$, under the matrix of the homogeneous transformation matrix ${}^0_7T$, with $Rot(Z,\gamma), Rot(Y,\beta), Rot(Y,\alpha)$, we can get the Euler angles. These angles are in fact the rotation between marks 0 and 7 along the $X, Y$ and $Z$ axes.

$${}^0_7R = \begin{bmatrix} {}^0_7T_{11} & {}^0_7T_{12} & {}^0_7T_{13} \\ {}^0_7T_{21} & {}^0_7T_{22} & {}^0_7T_{23} \\ {}^0_7T_{31} & {}^0_7T_{32} & {}^0_7T_{33} \end{bmatrix} = \begin{bmatrix} c_\gamma c_\beta c_\alpha - s\gamma s\alpha & -c_\gamma c_\beta s_\alpha - s_\gamma s_\alpha & c_\gamma s_\beta \\ c_\gamma c_\beta c_\alpha - s\gamma s\alpha & -s_\gamma c_\beta s_\alpha - c_\gamma c_\alpha & s_\gamma s_\beta \\ s_\beta c_\alpha & s_\beta s_\alpha & c_\beta \end{bmatrix} \tag{1.5}$$

$$\alpha = q_7, \beta = q_6, y = q_2 + q_3 + q_4 + q_5 \tag{1.6}$$

From formulas (1.4) and (1.6) we obtain the following inverse kinematics relations:

$$\begin{bmatrix} q_6 \\ q_1 \\ q_2 \\ q_3 \\ q_4 \\ q_5 \\ q_7 \end{bmatrix} = \begin{bmatrix} \beta \\ Z + L_4 c_6 - L_2 \\ \gamma - q_3 - q_4 - q_5 \\ \gamma - q_2 - q_4 - q_5 \\ \gamma - q_2 - q_3 - q_5 \\ \gamma - q_2 - q_3 - q_4 \\ \alpha \end{bmatrix} \tag{1.7}$$

## 1.7 Dynamic modeling of the ANAT robot according to the Lagrange method

In this part, we give a brief theoretical reminder of the Lagrange equations as well as the potential and kinetic energies necessary for the application of this method.

Then, we give the general shape of the dynamic modeling of a robot, and finally we apply it to realize the dynamic modeling of the ANAT robot.

### 1.7.1 Lagrange equations

The kinetic energy $K$ depending on the speeds of the joints $q_i$. The variation in kinetic energy takes the following form:

$$\delta K = (\frac{\partial K}{\partial q} - \frac{d}{dt}\frac{\partial K}{\partial \dot{q}})\partial q \tag{1.8}$$

The work variation takes the following form:

$$\delta W = \sum F^T \delta x = \sum F_i^T \frac{\partial f}{\partial q}\delta q = Q^T \delta q \tag{1.9}$$

By summing these two variations and integrating them between the times $t_1$ and $t_2$, we obtain the following expression:

$$\int_{t_1}^{t_2} (\delta K + \delta W)dt = \int_{t_1}^{t_2} (\frac{\partial K}{\partial q} - \frac{d}{dt}\frac{\partial K}{\partial \dot{q}} + Q^T)\delta q dt \tag{1.10}$$

According to the Hamilton principle, by canceling this variation, we obtain the dynamics of the system. The variation $\delta q$ being arbitrary, the integral is canceled if and only if the Lagrange equation is respected, that is to say if:

$$Q = \frac{d}{dt}\frac{\partial K^T}{\partial \dot{q}} - \frac{\partial K^T}{\partial q} - Q = 0 \tag{1.11}$$

Or $Q = -\frac{dU}{dq} + \tau + Q_{nc}$

With:

$U$ : Representing the potential energy;

$\tau$ : Representing the torque applied to the robot;

$Q_{nc}$ : Representing the non-conservative forces (ex: friction).

### 1.7.2 Representation of kinetic energy

The kinetic energy of a body $i$ is given by the following relation:

$$K_i = \frac{1}{2}\int (v_x^{ci})^T v_x^{ci} dm_i \tag{1.12}$$

With: $v_x^{ci}$ the speed of an element of mass $dm_i$ located at a distance $x$ from the center of inertia $c_i$ of the body $i$ where the reference of the object is located. After integration, we obtain the kinetic energy of a body $i$:

$$K_i = \frac{1}{2}(m_i v_{ci}^T v_{ci} +^{ci} w_{ci}^T I_i^{ci} w_{ci}) \tag{1.13}$$

Where:

$m_i$ : Represents the mass of body $i$;

$v_{ci}$ : Represents the linear speed of body $i$ expressed in the reference $O$;

$w_{ci}^{ci}$ : Represents the angular speed of body $i$ expressed in the reference $i$;

$I_i$ : Represents the tensor of inertias. If the orientation of the reference of the body is chosen so that it corresponds with the main axes of this same body, then the inertia tensor has the value:

$$I_i = \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix} \tag{1.14}$$

### 1.7.3 Representation of potential energy

The potential energy can be expressed in the following form:

$$U_i = -\int ({}^0g)^T \quad {}^0x dm_i \tag{1.15}$$

${}^0g^T$ : Represents the gravity vector expressed in the base frame.

${}^0x$ : Represents the position of a unit of mass $dm_i$.

If the reference is located at the center of mass $c_i$, $U_i$ has for value:

$$U_i = -{}^0g^{T\,0}c_i m_i \tag{1.16}$$

### 1.7.4 General shape of the dynamic model

The general form of a dynamic modelization obtained by the method of Lagrange is written as follows:

$$M(q)\ddot{q} + F(q,\dot{q}) = \tau \tag{1.17}$$

$M$ : Represents the mass matrix;

$F$ : The vector of centrifugal, Coriolis, friction and gravity forces;

$\tau$ : The torque applied to the robot joints.

### 1.7.5 Definition of the gravity vector and the dynamic specifications

For our robot, we consider that the center of mass of the different members is located at their extremities. So we get the dynamic specification table (1.4). The expression of

Table 1.4 – Dynamic specification table

| $Articulation$ | $cm_x$ | $cm_y$ | $cm_z$ | $m$ | $I_{xx}$ | $I_{yy}$ | $I_{zz}$ |
|---|---|---|---|---|---|---|---|
| 1 | $L_1$ | 0 | 0 | $m_1$ | $I_{xx1}$ | $I_{yy1}$ | $I_{zz1}$ |
| 2 | $L$ | 0 | 0 | $m_2$ | $I_{xx2}$ | $I_{yy2}$ | $I_{zz2}$ |
| 3 | $L$ | 0 | 0 | $m_3$ | $I_{xx3}$ | $I_{yy3}$ | $I_{zz3}$ |
| 4 | $L$ | 0 | 0 | $m_1$ | $I_{xx4}$ | $I_{yy14}$ | $I_{zz4}$ |
| 5 | $L_3$ | 0 | $L_2$ | $m_5$ | $I_{xx5}$ | $I_{yy5}$ | $I_{zz5}$ |
| 6 | $L$ | $-L_4$ | 0 | $m_6$ | $I_{xx6}$ | $I_{yy6}$ | $I_{zz6}$ |
| 7 | $L$ | 0 | $-L_5$ | $m_7$ | $I_{xx7}$ | $I_{yy7}$ | $I_{zz7}$ |

the vector of gravity, in the reference of the base, takes the following form:

$g = [o \quad o \quad -g]^T$

### 1.7.6 Kinetic energy of the ANAT robot

The kinetic energy of the ANAT robot is equal to the sum of the kinetic energy of the different members of the robot.

$$K = \sum_{i=1}^{7} \frac{1}{2}(m_i v_{ci}^T v_{ci} + {}^{ci} w_{ci}^T I_i^{ci} w_{ci}) \tag{1.18}$$

### 1.7.7 Potential energy of the ANAT robot

The potential energy of the robot is equal to the sum of the potential energy of the different members.

$$U = -\sum_{i=1^7} {}^0 g^{T\,0} c_i m_i \tag{1.19}$$

After calculation we find the following expression for the potential energy:

$$U = g[q_1(m_1+m_2+m_3+m_4+m_5+m_6+m_7)+c_6(m_6L_4-m_7(L_4+L_5))+L_2(2m_5+m_6+m_7)] \tag{1.20}$$

### 1.7.8 General shape of the dynamic model of the ANAT robot

After applying Hamilton's principle using the expressions for potential and kinetic energies, and putting this equation in general form, we get the expressions for $M$ and $F$.

$$M(q) = \begin{bmatrix} M_{11} & M_{12} & M_{13} & M_{14} & M_{15} & M_{16} & M_{17} \\ M_{21} & M_{22} & M_{23} & M_{24} & M_{25} & M_{26} & M_{27} \\ M_{31} & M_{32} & M_{33} & M_{34} & M_{35} & M_{36} & M_{37} \\ M_{41} & M_{42} & M_{43} & M_{44} & M_{45} & M_{46} & M_{47} \\ M_{51} & M_{52} & M_{53} & M_{54} & M_{55} & M_{56} & M_{57} \\ M_{61} & M_{62} & M_{63} & M_{64} & M_{65} & M_{66} & M_{67} \\ M_{71} & M_{72} & M_{73} & M_{74} & M_{75} & M_{76} & M_{77} \end{bmatrix} \tag{1.21}$$

$$F(q,\dot{q}) = \begin{bmatrix} F_{11} \\ F_{21} \\ F_{31} \\ F_{41} \\ F_{51} \\ F_{61} \\ F_{71} \end{bmatrix} \tag{1.22}$$

Now that we have carried out the modeling of the robot, we will subsequently work on five joints to detect and isolate faults as well as for the fault tolerant control.

$$M(q) = \begin{bmatrix} M_{11} & M_{12} & M_{13} & M_{14} & M_{15} \\ M_{21} & M_{22} & M_{23} & M_{24} & M_{25} \\ M_{31} & M_{32} & M_{33} & M_{34} & M_{35} \\ M_{41} & M_{42} & M_{43} & M_{44} & M_{45} \\ M_{51} & M_{52} & M_{53} & M_{54} & M_{55} \end{bmatrix} \tag{1.23}$$

$$F(q,\dot{q}) = \begin{bmatrix} F_{11} \\ F_{21} \\ F_{31} \\ F_{41} \\ F_{51} \end{bmatrix} \tag{1.24}$$

## 1.8 Conclusion

This chapter describes a state of the art concerning the various models cited and applied to an open serial structure.The robot we are controlling uses the ANAT technology, known as ANAT. Furthermore we present the geometric model of manipulator robot, then, the modeling of the robot ANAT, therefore, the inverse and direct kinematics. Finally, the dynamic modeling of the ANAT robot according to lagrange method.

# CHAPTER 2

# FAULT DETECTION AND ISOLATION AND FAULT TOLERANT CONTROL: STATE OF ART

Monitoring is only one module of a complete process allowing an installation to operate while respecting criteria of safety, productivity, and quality even in the presence of failure. System control can be designed to use the information provided by the monitoring module. This is then referred to as FTC. This chapter is devoted to the principle of fault detection and isolation. First, we will present the different types of defects in an industrial process and their models. Next, we will discuss the method of model-based approaches FDI to detect and isolate faults, followed by an analysis of residual generation to introduce the model-based diagnostic method for FTC. Furthermore, we will describe the main concepts of FTC, including the different methods and approaches used in the field. Then, the disadvantages and advantages of each method are presented. Finally, this presentation will permit us to position our method among the fault-tolerant control methods already described. A classification of faults will be given. Then, we explain the different approaches for fault tolerant control.

## 2.1 Definition of fault detection and isolation

A diagnosis is an explained state of a physical system compatible with the information available on the actual behavior of the system and with the available reference behavior model. Commonly, the diagnosis is expressed by component states [33] or the state of behavioral description relationships [34].
fault detection and isolation is a delicate operation since it is necessary, in a context subject to unpredictable operating circumstances of the system and to environmental disturbances, to decide whether there is a fault or not. Indeed, detectability is defined as being the ability of the diagnostic system to be able to discover the presence of a fault on a dynamic system. It is strongly linked to the notion of fault indicators which are called

residues generated by a residue generator which must, in a certain way, be sensitive to the failure that one wishes to detect. Generally, a compromise will have to be established between the number of false alarms and that of non-detection.
Regarding the isolability, we can say that it is the ability of the diagnostic system to find the origin of the fault. Usually, a failure produces a cascade of alarms which makes it difficult to isolate the failing component. The ability to isolate faults is linked to the structure of the calculated residuals and to the detection procedure implemented.
So the problem of fault detection and isolation is to measure the data during the actual operation of the system and generate the residuals to determine whether the operation of the system is normal or faulty after a comparison with the nominal system.

## 2.2 Definitions and concepts

To facilitate the understanding of the rest of this thesis, we introduce the following definitions [101]:

- Anomaly: A feature that does not conform to natural or logical law.
- Failure: A failure is a permanent interruption in the ability of the system to perform its required function. It is beyond failure because it involves a total shutdown of the system.
- Fault: Is a behavioral anomaly within the system. This concept is important in monitoring operations for the control and maintenance of industrial processes. Any deviation between the observed characteristic and the reference characteristic is considered to be a fault. It is therefore clear that a failure leads to a fault. But a fault does not necessarily lead to a failure. This is because the device can retain its ability to perform its main task if the faults do not have an impact on this task.
- Perturbation: Consists of any phenomenon conceived as normal influencing a process, not or badly, represented by a reference model.
- Error: It is defined as the difference between a measured or estimated value of a variable and a value given by a model and which is theoretically correct.
- Residual or fault indicator: It expresses the inconsistency between the available information and the theoretical information provided by a model.

• Modeling of the fault: This is the determination of a mathematical model to describe a specific effect of the fault.
• Qualitative model: It is a system model that describes behavior with relationships between variables and system parameters in heuristic terms such as causalities or rules.
• Quantitative model: It is a system model that describes behavior with relationships between variables and system parameters in analytical terms such as differential or difference equations.
• Threshold: This is the limit value for the deviation of a residue from zero, so if it is exceeded, a fault is declared as detected.
• Fault detection: this is the determination of the presence of a fault and the time of its occurrence.
• Fault isolation: This is the determination of the type and location of the fault.
• Fault identification: This is the determination of the size and temporal behavior of a fault.
• Diagnosis: It is the determination of the type, size, location and time of occurrence of a fault, it follows the detection of faults and includes isolation and identification.
• Monitoring: This is a continuous task, carried out in real time, of determining the state of a physical system, which consists of recording information and recognizing and indicating behavioral anomalies.
• Supervision: This is the monitoring of a physical system and the making of appropriate decisions in order to maintain its operation when faults appear.

## 2.3 Fault detection and isolation procedure

### 2.3.1 Different fault structures

Generally, a fault is characterized by a deviation from the normal operation of a system which is circumvented either by control signals or measurement signals. The faults affecting a system are evolving, of different natures and types.

### 2.3.2 Evolution of faults

Faults in figure (2.4) can be differentiated according to their shape and behavior over time [35]. Indeed, they can arise or already be present on the system; they can be of low or high amplitude, be abrupt or rather arrive gradually in the form of slow drifts. Since the appearance that defines them is known, they are said to be deterministic. On the other hand, the defects manifesting themselves intermittently are said to be stochastic. Because they can only be characterized by random evolutions.
Generally, there are three types of defects in the literature:
• Abrupt or abrupt fault (a): It is characterized by its discontinuous temporal behavior, it corresponds to a sudden failure: total or partial malfunction.
• Intermittent fault (b): This fault is a special case of abrupt fault with the particular property that the signal returns randomly to its nominal value. This type of fault characterizes false contacts or an intermittent failure of the sensors.
• Slow or gradual drift fault (c): This fault has a slow temporal behavior which makes it difficult to detect, it is characteristic of soiling or wear of a part.

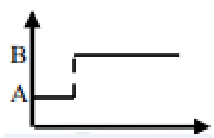


Figure 2.1 – Sudden fault

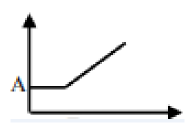


Figure 2.2 – Progressive fault

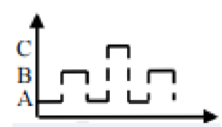


Figure 2.3 – Intermittent fault

Figure 2.4 – Distribution of defects according to their form

### 2.3.3 Nature of faults

The faults can be classified as faults of a multiplicative nature or of an additive nature figure (2.5), according to their effects on the performance of the system.

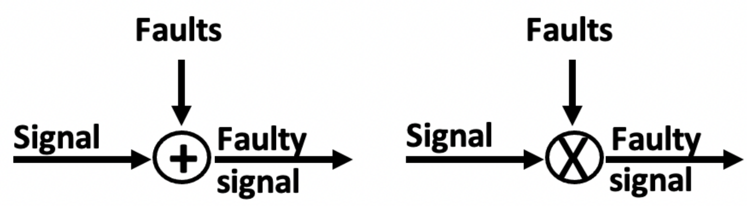



Figure 2.5 – Classification of faults: Additives and multiplicatives

• Multiplicative faults (a): faults in process dynamics are modeled by multiplicative faults. They correspond to the parametric modifications of the model representing the system. These induce changes in the correlation of the output signal of the system, as well as changes in the dynamics of the system.
• Additive faults (b): these faults are modeled as additive terms in the system model. They influence his condition or exit. This modeling is usually attributed to sensor and actuator faults.

### 2.3.4 Type of faults

As is known, commonly for the diagnostic procedure, modeling is used to characterize the system to be monitored and an effort is always made to define a model that better represents its operation. However, we must take into account the fault modeling when the system is affected by a fault. And subsequently, we need to differentiate these defects according to their nature. Indeed, they can affect the process, the actuators or the sensors. As shown in figure (2.6), three types of faults can affect the different elements of a system.

#### Actuator faults

Actuator faults act at the operative part and thus deteriorate the input signal of the system. 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 "stuck" in a position resulting in an inability to control the system through that actuator. Partial actuator faults are actuators reacting similarly to nominal control but only partially, that is to say with some degradations in their actions on the system.

### Sensor faults

These types of faults are the cause of a poor picture of the physical state of the system. A partial sensor fault produces a signal with more or less agreement with the true value of the variable to be measured. This can result in a reduction in the displayed value from the true value, or the presence of bias or increased noise preventing a good reading. A total sensor fault produces a value that is not related to the quantity to be measured.

### System or component faults

These are faults that appear in the components of the system itself, i.e. faults that cannot be classified either as sensor faults or as faults actuators. They represent changes in the parameters of the system, which induces a change in the dynamic behavior of the latter. As also, faults can be classified with respect to their effects on system performance.

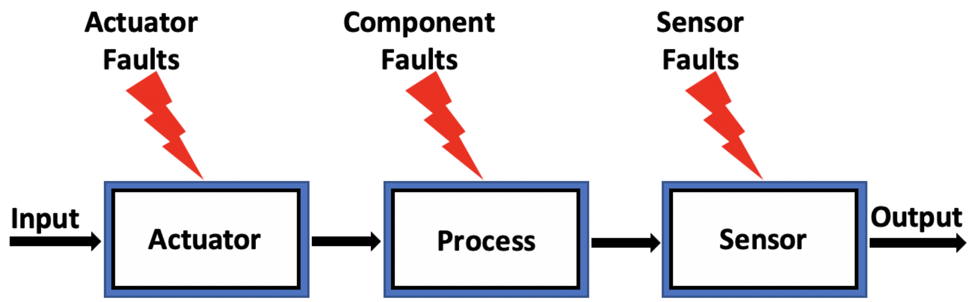



Figure 2.6 – Types of faults

## 2.4 Principle and classification of fault diagnosis methods

In the field of Engineering Sciences, the term diagnostic refers to the analysis of malfunctions and failures of a system in order to determine their nature and cause. Indeed, diagnosis is the process of evaluating a given operating state. This state is compared with a reference state, if the difference is not zero then it is an evaluation of operating drift. The diagnosis incorporates various steps, the first of which is to detect this operating state, once the anomaly is detected, we move on to the assessment of the causes of its occurrence which consists of identifying, analyzing and locate these causes; and finally the decision of action to modify it [36].
In the following study, it will be a question of presenting the principle of diagnosis and the different methods of fault detection and isolation.

### 2.4.1 Physical and analytical redundancy

#### 2.4.1.1 Physical redundancy

The most direct way to obtain reliable information on the same variable is to have several sensors measuring it simultaneously. A three-way redundancy makes it possible in particular to isolate a faulty sensor. This is shown by the advantage of the method by physical redundancy, which is conceptually simple, but this method suffers from the disadvantages which limit its application:
• Doubling or tripling the number of sensors increases the cost, leads to installation size problems and more charges to maintain them. Therefore, it is only used to monitor critical subassemblies of a system.
• Identical components manufactured in the same series may deteriorate in the same way and fail at the same time.

#### 2.4.1.2 Analytical redundancy

This redundancy makes use of analytical models representative of causal relationships and other existing constraints between the signals present in the system. The measurements obtained from the various sensors obscuring the system can then be linked by these models. The analytical models being a mathematical representation of the laws of evolution of the physical variables of the system is described by a set of equations resulting from the laws of physics. Thus, the process does not often follow such an ideal representation, this is due to the presence of uncertainties on the parameters of the model, structural modifications of the system, non-linearities and finally the effect of disturbances and measurements noise.

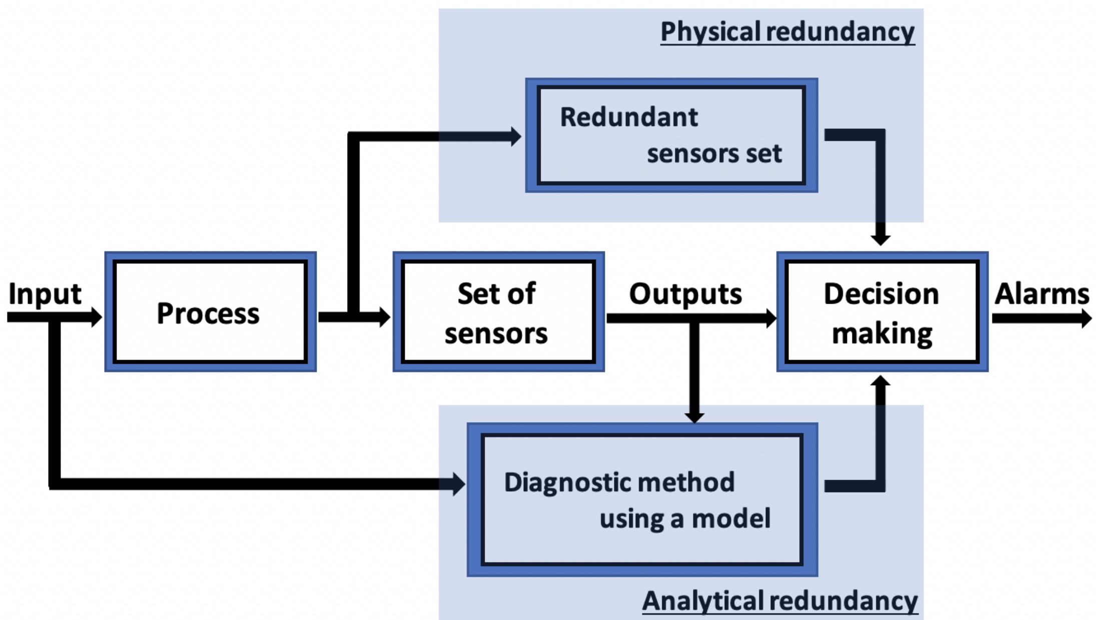



Figure 2.7 – Physical and analytical redundancy architecture

### 2.4.2 Presentation of diagnostic methods

The diversity of approaches that have been developed for the diagnosis of dynamic systems seems to be the result of different contexts. These contexts are associated with the nature of the targeted applications and with the specific characteristics of the resulting specifications. Thus, the nature of the information available on the system or the type of fault to be detected lead to the implementation of specific strategies. In this context, works on fault detection and isolation and those dedicated to diagnostics [37, 38, 39, 40], show a great variety both in the points of view and in the methods used.

Thus, they are mainly based on two approaches that we can classify as methods with or without models figure (2.8). In the first case, we use information redundancies and the knowledge provided by the mathematical model to define the mode of operation and decide whether the state of the system is normal or abnormal. These models can be of the quantitative type, expressed in the form of mathematical equations or else of the qualitative type, expressed for example in the form of logical relations.
On the other hand, the second case is based on the analysis of the data provided by the system which makes it possible to decide on its state based either on available measurements of signals from of the process, or on a priori knowledge concerning its behavior. We can cite, for example, the fuzzy logic approach [41], the artificial neural networks (ARN) approach [42] and the stochastic analysis of signals [43].

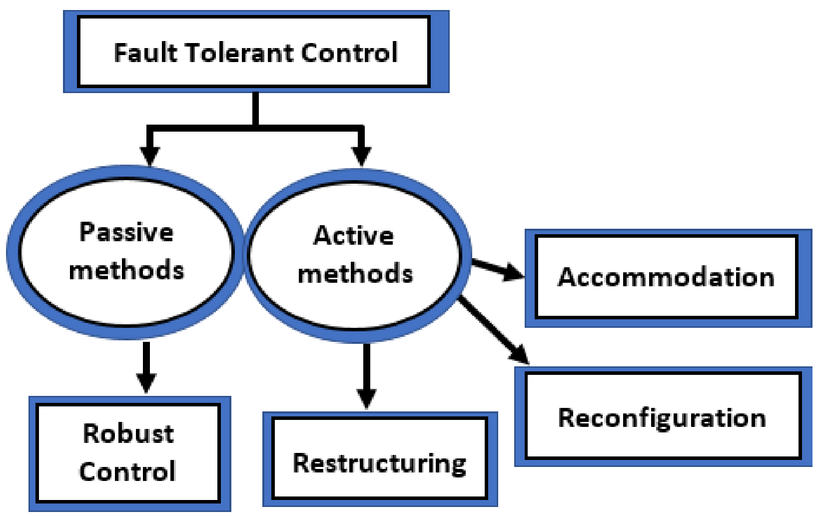



Figure 2.8 – Methods of fault detection and isolation

#### 2.4.2.1 Methods without models

In some cases, it turns out to be difficult or sometimes impossible to find the right mathematical model for a real system, because of the many reconfigurations involved in the production process or the complexity of the phenomena involved. The solution

in this case is the use of methods which do not require any in-depth knowledge of the system.
Indeed, we find:
• Quantitative approaches which are based on data processing.
• Knowledge-based qualitative approaches.

#### 2.4.2.2 Quantitative approaches

The data processing methods consist of the exploitation of a symbolic knowledge base. The only information available, in this case, is in the form of historical data which corresponds to the various modes of operation of the system or by means of on-line processing of signals from sensors.

#### 2.4.2.3 Qualitative approaches

These methods are knowledge-based, they can be considered when obtaining an analytical model of the process proves difficult, and when most of the measurements are unavailable. They are based on associative knowledge dependent on the system and on a priori knowledge of faults and their effects.

#### 2.4.2.4 Methods with models

Model-based approaches figure (2.9) are based on explicit behavioral models of the system being diagnosed. A great advantage of these approaches over relational and data processing approaches lies in the fact that only the information of the normal behavior of the process is taken into account through a reference model. The precision of the model, linked to the needs of the surveillance and to the diagnostic performance criteria, defines the choice of the use of quantitative or qualitative models. According to L. Travé-Massuyés et al. [44], model-based diagnostic methods also have the following advantages:
• Knowledge of the system is decoupled from diagnostic knowledge, This is knowledge of design rather than operation,

• The cost of development and maintenance is lower,

• The models provide adequate support for the explanation (the structure of the system is explicitly represented).

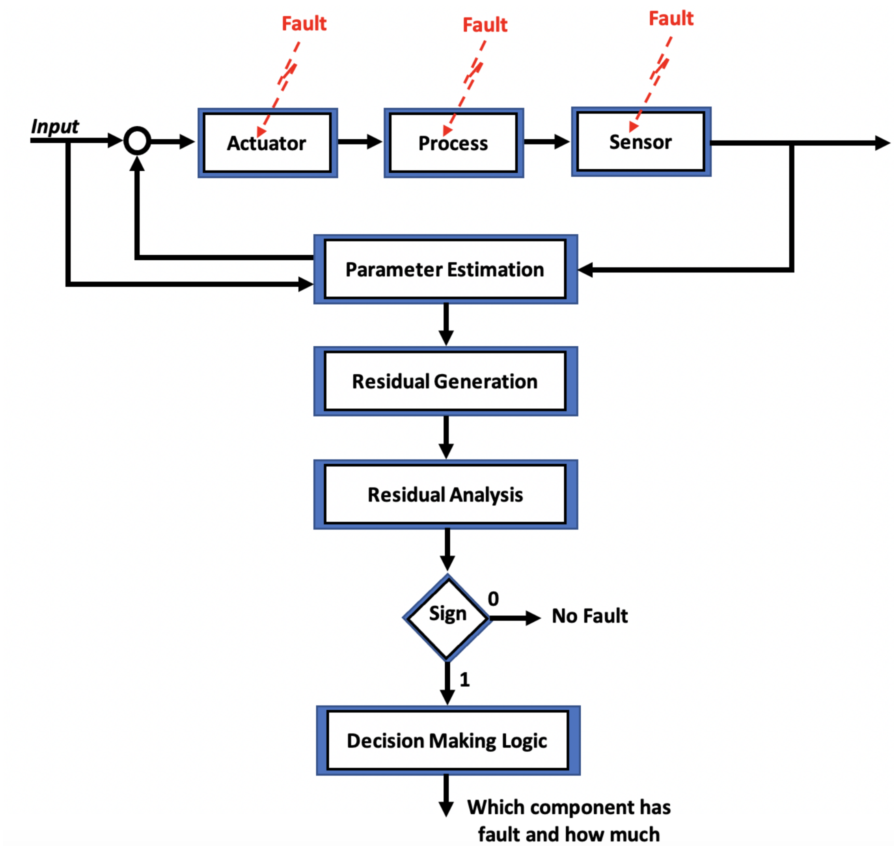



Figure 2.9 – General structure of fault detection and isolation (FDI)

The first work in the field of diagnostics based on dynamic models date back to the beginning of the 1970s with a strong "Kalmanian" influence [45].

Since then, many studies regularly take stock of the progress of different approaches that we can classify according to two main branches: qualitative approaches and quantitative approaches figure (2.8).

#### 2.4.2.5 Qualitative approaches

The Artificial Intelligence (AI) community has proposed approaches that use deep knowledge of system components based on a logical theory of reasoning [46]. Fundamental analysis considers obtaining consistency between the observations and the model by removing assumptions about the behavior of some components [47]. Modeling based on qualitative reasoning and causal modeling are the two main trends proposed by this community.
Among the methods most used by this community, we can cite causal graphs, fuzzy logic and Petri nets.

#### 2.4.2.6 Quantitative approaches

Unlike AI approaches, the FDI community has proposed approaches that are based on the modeling and control of industrial systems with a quantitative dynamic model. This model is generally represented by differential equations or differences with a precision defined by the objective of the diagnosis.
FDI is the subject of our work, here it will be a question of presenting the different methods used, especially methods based on quantitative mathematical models.
At the start of the 1970s, research was mainly focused on the aeronautics sector, then following the rapid progress of several research sectors, FDI approaches have been the subject of a particular boom and various solutions have been developed. developed to improve the efficiency, operational safety and reliability of industrial process automation.
FDI techniques are based on a mathematical model of the system and are based on a comparison of system measurements with information from the model [48]. Particularly important tasks in the surveillance activity are the detection, isolation and identification of faults. These tasks which consist of determining whether or not there are any faults and if so, determining the origin of the faults which may be either: A failure of sensors or actuators or a malfunction of the system.
Whatever the FDI method used, in order to make the most of the information contained

in the measurements taken from the process, this task figure (2.10) can be broken down into the following three steps:

• Generation of residuals: Generally speaking, a residual corresponds to the difference between the measured output and the observed output. The amplitude of the residual signal obtained at the output of the generator therefore indicates the occurrence or not of a fault. The fault detection is subsequently based on the evaluation of these different generated residues.

• Evaluation of the residuals: the residuals are the signals that carry information on the duration and occurrence of faults, based on the difference between the measurements and the calculations from the model. These residues are compared against the previously defined limits. The problem of evaluation is to define the threshold in order to detect the presence of changes. In normal operation, the residues are zero and they deviate from zero in the presence of faults.

• The decision: it constitutes the last step of the diagnostic task. It makes it possible to identify faults, that is to say to locate the cause of the anomaly in the system.

Thus these detection and isolation methods based on mathematical models generally rely on the generation of residues. To obtain the analytical expressions residuals, several techniques can be used. We mainly find those using parity space, parametric estimation or state estimation [49, 50].

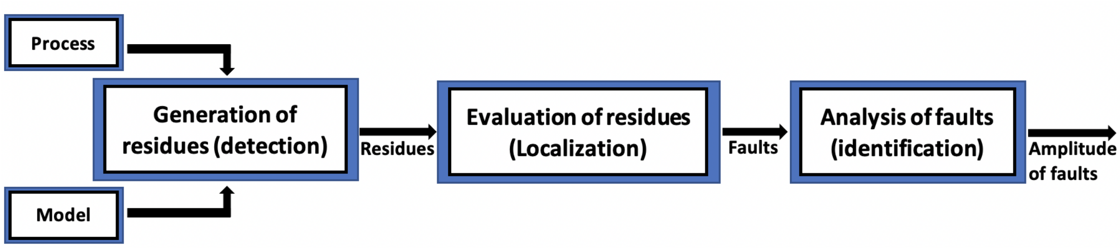



Figure 2.10 – Fault detection and isolation procedure

• Parity space: The methods based on parity relations, [51, 52], are based on the development of signals making it possible to test the consistency of measurements with respect to their values calculated using a model, that is, verifying the parity of the process model with the measured outputs and known inputs of the model. The design of the parity space is based on the development of analytical expressions. Residuals are generated by employing parity equations which are obtained by reconstructing the structure of the model and transforming the variables of the system. The rewriting of the model is equivalent to eliminating the unknown variables from the initial model, for that two approaches are possible. The first geometrical based one uses a projection mechanism [51] and we can only apply this approach for linear systems. The second, [53, 54], uses elimination theory as a mathematical tool and is only used for polynomial dynamical systems. Generally, these methods have been studied for linear, bilinear and other state systems affine. A few cases for nonlinear dynamical systems have been studied by Staroswiecki et al. [55], but they are always limited to the case of algebraic systems.

• Parametric estimation: The approach based on estimation of model parameters [56, 57, 58, 59], allows to analyze the influence of defects on the structural parameters of the system model. The basic idea of this method is to continuously estimate process parameters using input-output measurements and compare them to normal process state parameters. For this, we must establish a mathematical model of the system to be diagnosed and describe all the relationships that exist between the physical constants and the parameters of the model. Parametric estimation has the advantage of providing information on the importance of the deviations. However, one of the major drawbacks of the method lies in the increase in the size of the vector of parameters as the number of defects increases, which makes it difficult to calculate to estimate this vector. In addition, the relationships between physical and mathematical parameters are not always invertible, which complicates the task of isolation.

• State estimation: These methods [60, 61, 62, 63], are based on the use of state observers. They are based on a good knowledge of the model and its parameters, they consist in estimating the state variables by an observer for reconstruct information. An observer is a dynamic system having a structure similar to that of the model of the system studied but it differs from an additive term which is an adaptation term making it possible to correct the difference between the output of the observer and that of the system real and ensure stability. The basic idea is to estimate the outputs of the process using an observer or a Kalman filter, then the generation of the residuals is obtained by making

the difference between the measured outputs and their estimates.
These methods are very effective in detecting and isolating faults. Indeed, the first results on observers for linear systems were studied by KalmanBucy in 1961 [64] and Lunberger in 1966 [65]. And since then, this problem has continued to be one of the main interests of researchers and mainly for nonlinear systems [66, 67, 68, 69, 70].
Depending on the nature of the problems to be dealt with, these observers can be classified into three main categories which are: stochastic observers (DMZ filters [71] and particle filters [72]), deterministic observers (Luenberger observers [73], high gain observers [74], algebraic observers [75], sliding horizon observers [76] and intelligent observers [77]) and finally adaptive observers [78] (interval observers [79], parallel observers [80] and multi-model observers [81]).

## 2.5 Robustness and performance of diagnostic methods with models.

Choosing one of several fault detection and isolation methods depends on various factors that we need to consider. We can cite, a priori, the presence or not a mathematical model that can well describe the behavior of the system to be diagnosed. Therefore, the modeling of a system requires a good knowledge of its behavior, namely the non-linearities, the type of faults to be detected, the presence of noise or measurement uncertainties,. . . .
The model-based diagnostic method consists in comparing the quantities deduced from a model representative of the operation of the process studied with the measurements directly observed. The presence of a deviation provides an appreciation of an emerging anomaly.
The robustness of the diagnostic procedure depends on the degree of precision of the modeling adopted. The quality of the diagnosis therefore depends on the representativeness of the models used. The mathematical models generally used are complex and in the form of systems of partial differential equations or differential equations.
In general, the coefficients of these models are determined by parameter identification techniques from various experiments carried out on the process. The area of validity of

the diagnosis is then directly linked to the validity of the model, this is the main drawback of these methods based on the models. On the other hand, this approach has the big advantage of not making a priori assumptions about the faults capable of appearing on the different modules and also of being able to detect early degradation of performance. Depending on the nature of the models selected, it is possible to diagnose faults during transient operating phases.

The synthesis of the fault diagnosis principle by the parameter estimation method was made possible by considering the physical models of a process in the form of equations of state. Thanks to this state representation, it is possible to know all the internal states of the system. The objective of this representation lies in its generality. It can be used for both single and multi-variable systems. The methods of diagnosis by state estimation techniques [82] are adequate provided that the structure of the model accurately reflects the behavior of the system. Otherwise, the results of the estimates should be taken with great care. They have proved their worth mainly in the fields of space and aeronautics.

Furthermore, the diagnostic methods by parameter estimation apply to the very particular case where it is desired to follow the evolution of certain physical parameters critical for the operation of a process and which are not directly measurable. The general principle of these methods is to estimate the internal parameters. These approaches were initially developed by automation engineers who were looking for models of industrial systems and they have been the subject of extensive automation. Estimation diagnostic methods are very efficient when we have physical models. They fall into the family of internal diagnostic techniques where we are interested in knowing the evolution of internal parameters.

A diagnostic algorithm is said to be robust if the method used to generate the residuals takes into account the model uncertainties. In general, the mathematical model of a system, while precise and accurate in formulating and writing the equations, does not always describe how the system actually works. This can have different causes, that is that in reality, other parameters may intervene. Measurement noise and parametric uncertainties can generate false alarms or non-detections. The detection step is very important in the process of diagnosing systems. If this step is not performed correctly,

faults may be poorly or not detected; false alarms which correspond to the detection of a fault appear although no fault has occurred. Due to non-detection, a fault that will not be addressed could lead to more serious faults and lead to system malfunction, failures or even breakdowns and therefore to its complete shutdown.
The performance of a diagnostic algorithm is therefore quantified according to its percentage of false detections and non-detections. The compromise lies in the choice of the fault detection threshold which must be chosen so that we can detect even the weakest faults, while avoiding confusing disturbances and measurement noise with faults to be detected. Patton et al. [83] give more details about the performance of a detection and isolation system in which they define certain qualities such as the speed of detection and isolation and the minimization of false alarms and bad detections. In our work, we are interested in the use of approaches based on quantitative mathematical models.

## 2.6 fault tolerant control system

### 2.6.1 Objectives of the fault tolerant control

A fault tolerant system has the ability to maintain nominal goals despite the occurrence of a fault and to automatically cope with it. It makes it possible in particular to guarantee the stability of the system and \ or achieve the desired performance in the presence of faults [84, 85, 86]. Despite the fact that a conventional control scheme makes it possible to guarantee the stability and the desired 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 to instability, in the presence of a fault. To overcome such shortcomings, special control laws, taking into account the effect of the fault, have been developed with the specific aim of protecting the desired performance. In complex industrial applications such as aeronautics or nuclear, the problem of fault tolerance is often addressed by means of hardware redundancy.
This strategy is not only expensive but it also requires a large maintenance device. The fault tolerant control approached by analytical approaches, avoids high costs of financing and maintenance. The main task in a fault tolerant control system is the synthesis

of control laws with an adequate structure to guarantee the stability of the system and to maintain the control on performance close the desired one, not only when all the components of the control are operational, but also when there are sensor, actuator or system failures. The research work carried out in this context for two decades is numerous [87, 88, 89]. The principle of fault tolerant control is illustrated by the diagram in figure (2.11).

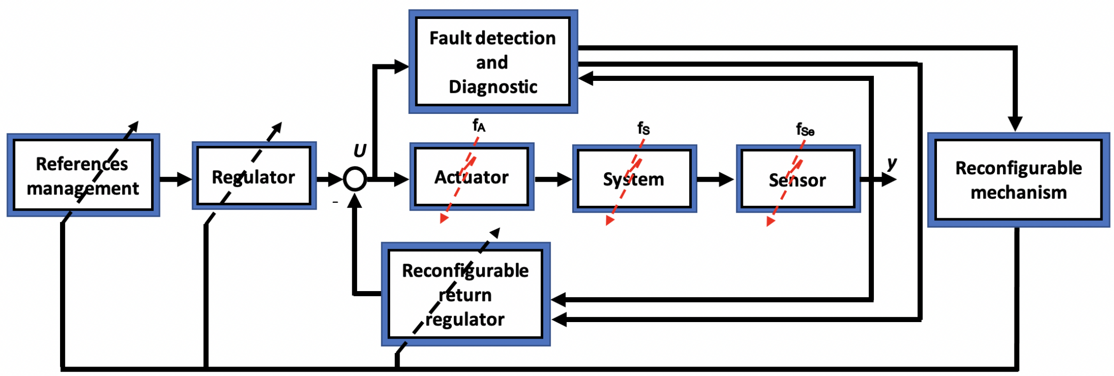



Figure 2.11 – Principle of a fault tolerant control system

## 2.7 Definition of Fault-Tolerant Controller

The FTC approaches are developed to improve the safety and reliability of control systems against fault and failures. A control system that can automatically compensate for a fault (and sometimes failures) effect in the system components while maintaining the system stability along with the desired level of overall performance is called an FTC system [90, 91, 92, 93]. Generally, based on the dependency on the fault information, FTC systems can be categorized into two main classes: passive FTC and active FTC. Passive FTC is an FTC system that does not rely on faulty information to control the system and is closely related to robust control where a fixed controller is designed to be robust against a predefined fault in the system [90, 94]. In general, redundancy is integrated into the passive fault-tolerant control design to make them resilient against faults [95]. In contrast with passive FTC systems, active FTC systems perform based on the occurred fault in the system. In such control systems, FDI unit is used to find the fault location and measure its size; then, a supervisory controller decides how to modify the control structure and parameters to compensate for the occurred fault in the system. Such modification can be varied from control reconfiguration [96, 97] to managing redundancies [98], and analytical redundancy [99, 100]. Both active and passive approaches use different techniques for the same purpose; however, due to their difference in their design approach, each approach may result in some unique properties.

## 2.8 Classification of the methods of the fault tolerant control

The methods of synthesis of fault tolerant control systems are generally classified into two large families: passive approaches (Passive Fault Tolerant Control Systems: PFTCS) and so-called active approaches (Active Fault Tolerant Control Systems: AFTCS). The passive methods are equivalent to the methods of synthesis of robust control laws. Active methods are generally classified as three subclasses: fault accommodation, system reconfiguration and restructuring [101]. The diagram in Figure (2.12) illustrates this classification.

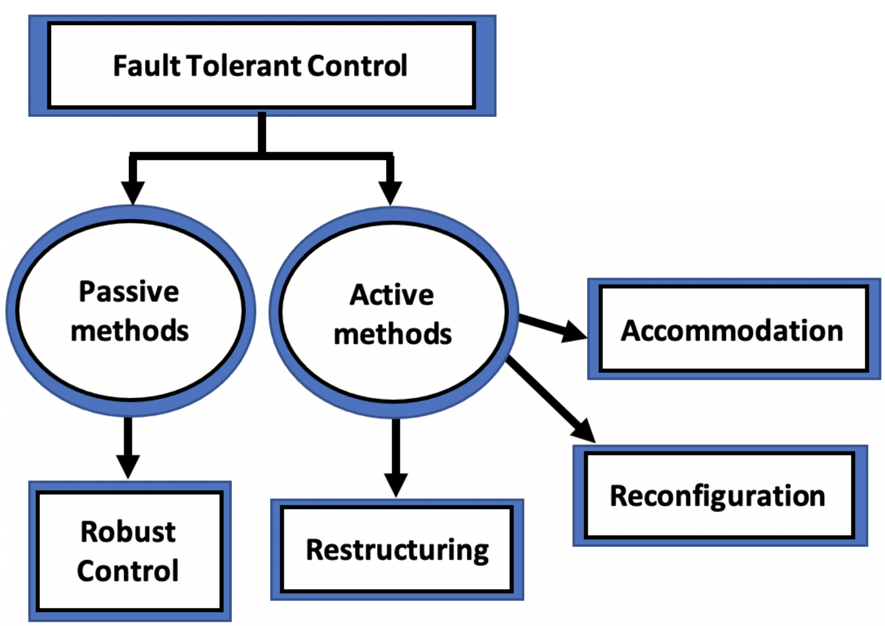



Figure 2.12 – Fault tolerant order classifications

### 2.8.1 Passive approach

In the passive approach, robust control techniques are used so that the closed loop system remains immune to a certain set of faults. Fault tolerance is ensured without the use of online information relating to faults affecting the system and without changing the structure of the nominal regulators [103, 104]. The faults, considered as being sources of disturbances, are then taken into account in the design of the control system figure (2.13). The synthesis of control laws, of the passive approach, is based on the use of robust control techniques with respect to parametric uncertainties and external disturbances (command $H_\infty$, command in sliding mode,...). To have a global view of the robust command methods, the reader can refer to this paper [265]. This type of approach does not need a diagnostic module to detect the presence of faults or a block of reconfiguration of the control law and/or system parameters [105].

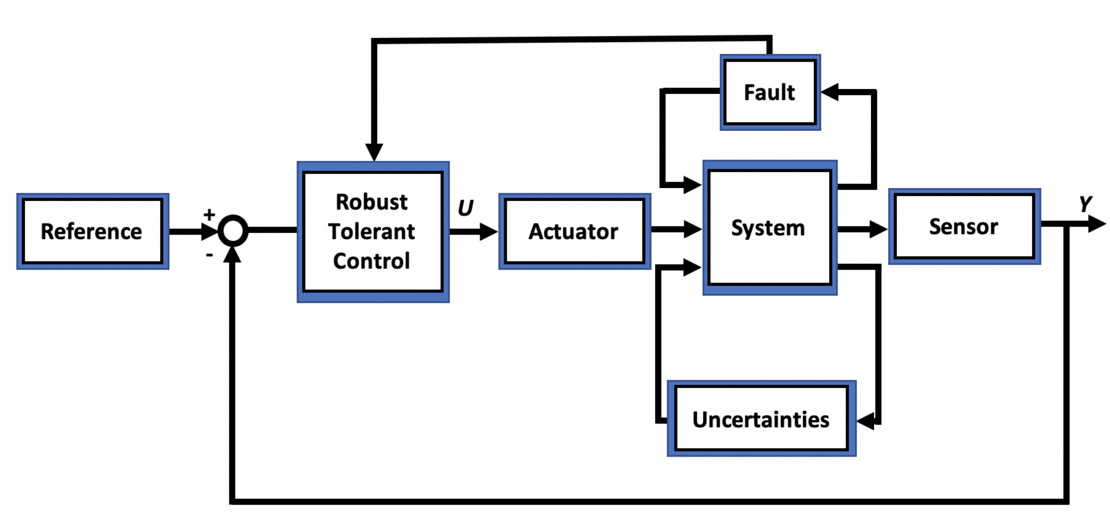



Figure 2.13 – Block diagram of a passive ftc control law

Many passive methods of FTC control, using robust control techniques based on criterion minimization, have been developed [106]. A methodology based on the minimization of an LQG (Linear Quadratic Gaussian) criterion for synthesizing the FTC corrector has been proposed [107]. In this methodology, the effect of faults on the system was modeled by a random process. In [272], the authors used the parametrization of

"Youla" and the "loop shapin" technique of the $H_\infty$ command to design a fault-tolerant control law. The minimization of a $H_\infty$ criterion in order to synthesizing fault-tolerant control laws has been considered in several works. In particular, the resolution of Riccati algebraic equations [273] and the inequalities Linear matrix [104] have been used to solve the $H_\infty$ minimization problem. Although the fault-tolerant control laws of the passive approach are simple to implement, they exhibit a low level of performance.
In fact, robustness to certain faults, which occur infrequently, is achieved at the expense of degraded performance in flawless mode of operation. It is obvious that this degradation in performance will be greater if the number of predefined faults is large. Passive techniques may be sufficient in some applications where the set of faults is small.

### 2.8.2 Active approach

The so-called active fault-tolerant control methods react to the occurrence of one or more faults by reconfiguring the control law online so as to maintain the stability and nominal performance of the system [110, 101, 111]. Effective fault detection and isolation tools are then required to detect and locate faults affecting the system online.
The general architecture of an active FTC control is shown in figure (2.14) The two blocks FDI and FTC, constitute the two important steps of the command.
• The FDI block uses the measured input and outputs of the system to detect and estimate, online, the fault as well as the system state variables. Once the fault has occurred, the FDI block provides online information about the fault and the status of the system to the "FTC" block. The FDI module must make it possible to take take into account the different types of faults occurring on the system and ensure the reliability of this information to activate the reconfiguration mechanism in minimal time.
• The FTC block is based on the information delivered by the FDI block. Depending on the mechanism used and the type of fault presented, it accommodates or reconfigures the control law online in order to maintain the stability and dynamics of the system as well as its nominal performance [105].
Figure (2.14) shows that the active FTC control contains a supervisor. Its principle is as follows: without fault, the nominal control which has been determined beforehand

for the "perfect" system rejects disturbances and ensures the stability of the loop system closed. In this case, the FDI block does not detect any fault and the control law will not undergo any change. If a fault occurs, the FDI block detects it, isolates it and identifies it. Then the FTC block gives a new control law capable of stabilizing the defective system. Generally, three types of configurations are possible: fault accommodation, system reconfiguration and restructuring. In the case of reconfiguration, only the low amplitude faults are taken into account. The new control law is generated by the online adaptation of the parameters of the inputs / outputs of the controller and the system to be controlled remains unchanged [236]. System reconfiguration is used in the event that the failing parts cannot be accommodated [112, 113, 114, 115]. It is characterized by the modification of the structure of the system in order to compensate for the defect. Restructuring consists in synthesizing a new control law by modifying the structure and parameters of the regulator [237]. It is used in the case where the control problem cannot be solved using accommodation or reconfiguration. The big disadvantage of the active approach is the limitation of the time available for recalculate the new control law at each fault detection [105]. Active FTC approaches are mainly categorized based on the FDI unit used in their design. However, the strategy used for the compensation of fault might be different. Here, a brief review of different fault compensation approaches used in active FTC design is presented.

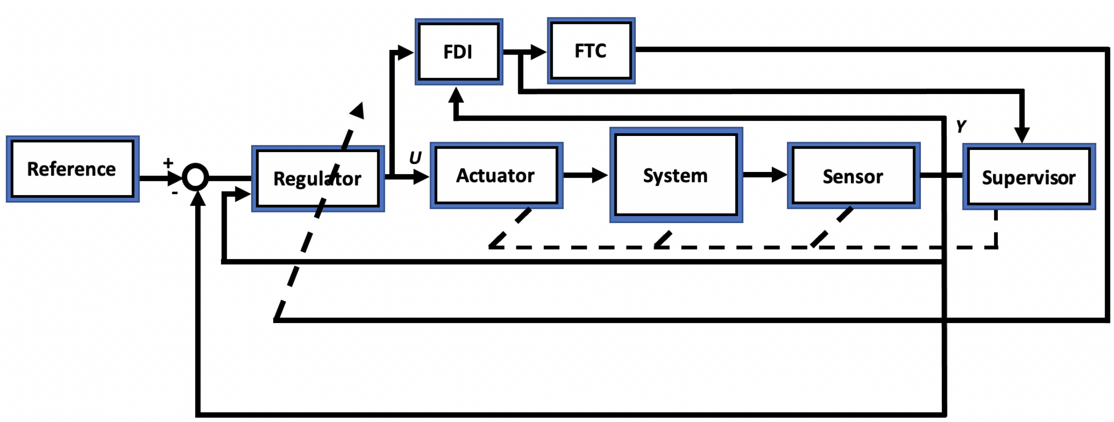



Figure 2.14 – Block diagram of an active ftc control law

#### 2.8.2.1 Switching-Based Active FTC

This kind of controller relies on a set of predefined candidate controllers and the system switches among them based on the fault type and severity. An important factor in designing a switching-based controller is the dwell time [100]. The dwell time is the lower band on the length of the time interval between the consecutive switching instances. It should be noted that the upper-bound is the detection interval (DI) which is the length of time in which the controller performance does not change after the fault occurrence. Allerhand and Shaked introduced an active FTC technique considering the dwelling time among switches which guarantees the stability of the system by solving linear matrix inequalities [116]. In [117], a switching-based controller without any extra models or filters is developed. In their design approach, the bounds of the state were guaranteed during the switching delays.

#### 2.8.2.2 Hierarchical Structure Active FTC

Hierarchal structures are applied in the integration of FDI and FTC in active FTC systems. In this strategy, after detection and isolation of the fault in the system, the controller can be reconfigured either by adaptive control strategies [118, 119], or receding horizon control [120].

#### 2.8.2.3 Safe Parking Active FTC

The concept of safe parking was first introduced by Gandhi and Mhaskar [121]. This concept is based on the idea of maintaining the system at a proper temporary equilibrium (safe parking) point in the presence of fault until the active controller pushes the states of the system to a nominal equilibrium point. Later, this work was further developed to choose a safe parking point using the FDI information [122]. Similarly, Paolo and Lafotune used this concept to propose a safe controllability method [123].

#### 2.8.2.4 Analytical Feedback Compensation Active FTC

Analytical feedback compensation strategies are based on the real-time fault detection and isolation [124, 125]. These approaches need very accurate FDI information with minimum delay. In [124], an adaptive neural network (NN) approach was used to detect faults in pressure valves of a proton exchange membrane (PEM) fuel cell. A nonlinear observer based on the nonlinear model of the observer was designed and was combined with an NN which its gains were updated using extended Kalman filter (EKF). This approach helped to find different faults in real time with sufficient accuracy and fault data was used as a feedback signal to eliminate the fault from the actuators.

In [126], an online recursive identification method was used for FDI and was integrated into a proportional–integral–derivative controller (PID) through a feedback signal to compensate for the fault in the system analytically. An active FTC system for a multi-agent leader-following system based on wavelet neural network (WNN) was designed [127]. In their work, a robust leader-follower controller based on graph theory was designed for the multi-agent system, then, the WNN-based FDI was used to compensate for the fault in the actuators through a feedback structure. In [125], an integral-type robust sliding mode controller was designed based on the feedback data from the iterative learning FDI unit which could map analytical redundancy in an optimal manner.

#### 2.8.2.5 Hybrid FTC

Hybrid FTC systems are introduced to leverage the advantages of passive and active FTC at the same time [128]. Based on this idea, the passive controller is used as a safe controller until a reliable controller based on the information received from the FDI unit is achieved. Based on this concept, the controller has more time to obtain accurate fault information, and optimal control reconfiguration can be performed without any concerns about system safety.

Table 2.1 – Comparison between AFTCS and PFTCS.

| System's Property | AFTCS | PFTCS |
|---|---|---|
| Architecture | Complex | Simple |
| Time Response | Slow | Fast |
| Fault Detection | Online/Real Time | Offline |
| Computations | Large | Relatively Small |
| FDI | Essential | Not Required |
| Controller Reconfiguration | Required | Not Required |
| Noise Effect | -Can be corrupted by noise and the wrong decision can be made | Robust to Noise |
| Time delay | Possible due to noise | No Time Delay |
| Faults nature | Various | Fixed predefined faults are accommodated |
| Control Structure | Variable | Fixed |

## 2.9 Conclusion

In this chapter, we unveiled the different failures that could affect an industrial system. Then, we presented the different fault detection and isolation techniques while featuring the model-based methods to generate the system's residuals. The FDI systems were deeply investigated and fundamentally illustrated. Then, we categorized FDI system based on the approaches used in their design into three main categories: model-based, knowledge-based, and combined model-knowledge-based approaches. The model-based approaches are simple to implement. However, their performance is highly dependent on the accuracy of the mathematical model of the system. On the other hand, the knowledge-based approaches are not reliant on the mathematical model of the system, but they need substantial historical data about the system performance for training purposes. The combined model-knowledge-based approach has less dependency on model accuracy and needs less training data; however, the design complexity would increase and prior knowledge of both approaches is required to design an efficient system. Then we discussed the advantages and disadvantages of each model and presented an overview of the different methods of synthesis of the fault-tolerant control law. The synthesis presented is certainly not complete, but we have endeavored to present the prominent trends that seem essential to us for the developments that will follow. These approaches are classified into two broad categories: passive approaches and active approaches.
The next chapter will present the methods of fault detection and isolation for robot manipulators for sensors and actuators.

# CHAPTER 3

# FAULT DETECTION AND ISOLATION FOR ROBOT MANIPULATOR

In the first part of this chapter, we present the FDI technique for robot manipulators based on high gain observers using the two methods for sensor fault detection. Then, a novel technique for actuator fault by applying high order sliding mode observer for FDI will be introduced.

## 3.1 High gain observer technique for sensor fault detection and isolation

### 3.1.1 Modelling

Consider the MIMO nonlinear system with $m$ inputs and $p$ outputs defined by the following state representation [129]:

$$\begin{cases} \dot{x} = f(x,d,t) + \sum_{i=1}^{m} g_i(x,t)u_i(t) \\ y = Cx \end{cases} \tag{3.1}$$

where $x \in \mathbb{R}^n$ is the state variable vector, $u(t) \in \mathbb{R}^m$ is the input control vector and $y \in \mathbb{R}^p$ is the output vector, f(x, d, t) is the n-dimensional unknown nonlinear dynamics and $d$ is the disturbance, $g(x,t)$ is the $(n \times m)$ nonlinear control dynamics matrix and $C$ is the $(p \times n)$ output distribution matrix. Such systems must satisfy the following assumptions:

A1 : The integers m, p and n are known such as $m \leq n$ and $p = m$;

A2 : The system is controllable and observable, in limit detectable and stabilizable;

A3 : The unknown nonlinear dynamics and unexpected disturbances are continuously differentiable with respect to the time variable.

The dynamics of n-DOF for robot manipulator in the following matrix equation:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + f(\dot{q}) = \tau + \tau_d \tag{3.2}$$

Where $q \in \mathbb{R}^n$ is the vector of the generalized coordinates in the joint space, $\dot{q}$, $\ddot{q} \in \mathbb{R}^n$

the joint velocity and acceleration vectors, respectively, $M(q) \in \mathbb{R}^{n\times n}$ is the inertia matrix, $C(q,\dot{q}) \in \mathbb{R}^{n\times n}$ is the centrifugal and coriolis matrix, $G(q) \in \mathbb{R}^{n}$ is the gravitational vector, $f(\dot{q}) \in \mathbb{R}^{n}$ is the vector of viscous friction torque at the joints, $\tau$, $\tau_d \in \mathbb{R}^{n}$ denotes the disturbance and torque input vectors, respectively.

The dynamic equation of the robot manipulator given in partitioned form in equation (3.2) can be rewritten as follows: with the disturbance and the viscous friction are negligible. ($\tau_d = 0$), ($F\dot{q} = 0$).

$$\ddot{q} = -M(q)^{-1}F(q,\dot{q}) + M(q)^{-1}\tau \tag{3.3}$$

where $M$ is the inertia matrix, which is symmetric and positive definite. Thus, $M(q)^{-}1$ always exits. $F$ is the centrifugal, coriolis, and gravity vector; q is the joint position vector; $\tau$ is the torque input vector of the manipulator. Let $x = [X_1^T, X_2^T]^T$ the state vector with $X_1 = [q_1, q_2, q_3, q_4, q_5]^T$ and $X_2 = [\dot{q}_1, \dot{q}_2, \dot{q}_3, \dot{q}_4, \dot{q}_5]^T$ , and $y = X_1$ is the output vector. The description of the system can be given in state representation form as follows:

$$\begin{cases} \dot{x}_1 = x_6 \\ \dot{x}_2 = x_7 \\ \dot{x}_3 = x_8 \\ \dot{x}_4 = x_9 \\ \dot{x}_5 = x_{10} \\ \dot{x}_6 = f_1(x,d,t) + \sum_{i=1}^{5} g_{1i}(x,t)u_i(t) \\ \dot{x}_7 = f_2(x,d,t) + \sum_{i=1}^{5} g_{2i}(x,t)u_i(t) \\ \dot{x}_8 = f_3(x,d,t) + \sum_{i=1}^{5} g_{3i}(x,t)u_i(t) \\ \dot{x}_9 = f_4(x,d,t) + \sum_{i=1}^{5} g_{4i}(x,t)u_i(t) \\ \dot{x}_{10} = f_5(x,d,t) + \sum_{i=1}^{5} g_{5i}(x,t)u_i(t) \end{cases} \tag{3.4}$$

where

$$g(x,t) = M(q)^{-1}$$

$$u_i = \tau_i \qquad for \qquad i = 1:5$$

$$f(x,d,t) = -M(q)^{-1}F(q,\dot{q})$$

### 3.1.2 High Gain Observer technique

In general, an observer is a dynamic system that provides estimations of the current state of the system, by using the previous knowledge of the inputs and outputs of the system.

Consider the following class of affine nonlinear system representing in (3.1). The system (3.1) has the input $u(t) \in \mathbb{R}^m$ which has a set of admissible values. It is also assumed that there exists a physical domain $\Omega \in \mathbb{R}^n$(open, bounded) of evolution of the input and that is the domain of interest of the system.

Suppose that system (3.1) is observable in the sense of rank and that $u = 0$ is an universal input, then the jacobian $\{h_1, L_f h_1, \ldots, L_f^{n-1} h_1, h_2, L_f^{n-1} h_2, L_f^{n-1} h_p\}$.

In the neighborhood of a regular point we can select a subset of full rank:

$$\phi = \{z_1, \ldots, z_n\}\{h_1, L_f h_1, \ldots, L_f^{n-1} h_1, h_2, L_f^{n-1} h_2, L_f^{n-1} h_p\} \tag{3.5}$$

with $\sum_{k=1}^{p} \eta_k = n$ and $L$ is the lie derivative.

The input $h_k(x)$ belongs in the order $\eta_k$. This determines a local coordinate system in which the system (3.1) is written as:

$$\begin{cases} \dot{z} = Az + \tilde{\varphi}(z) + \bar{\varphi}(z)u \\ y = Cz \end{cases} \tag{3.6}$$

with $z \in \mathbb{R}^n$, $u \in \mathbb{R}^m$, $y \in \mathbb{R}^p$

$$A = \begin{bmatrix} A_1 & & \\ & \ddots & \\ & & A_p \end{bmatrix}; \qquad C = \begin{bmatrix} C_1 & & \\ & \ddots & \\ & & C_p \end{bmatrix}; \tag{3.7}$$

$$\tilde{\varphi}(z) = \begin{bmatrix} \tilde{\varphi}_1(z) \\ \vdots \\ \tilde{\varphi}_p(z) \end{bmatrix}; \qquad \bar{\varphi}(z) = \begin{bmatrix} \bar{\varphi}_1(z) \\ \vdots \\ \bar{\varphi}_p(z) \end{bmatrix}; \tag{3.8}$$

with

$$A_k = \begin{bmatrix} 0 & 1 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 1 \\ 0 & 0 & \dots & 0 \end{bmatrix}; \qquad \tilde{\varphi}_k(z) = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ \tilde{\varphi}_k(z) \end{bmatrix}; \tag{3.9}$$

$$\bar{\varphi}_k(z) = \begin{bmatrix} \bar{\varphi_1} k(z) \\ \vdots \\ \bar{\varphi_{\eta_k}} k(z) \end{bmatrix}; \qquad C_k = \begin{bmatrix} 1 & 0 & \dots & 0 \end{bmatrix} \tag{3.10}$$

with $\tilde{\varphi}_k(z) = L_f^{\eta k} h_k$; $\quad \bar{\varphi}_i k(z) = L_g L_f^{i-1} h_k$; $\quad dim(A_k) = (\eta_k \times \eta_k)$; $\quad dim(C_k) = (1 \times \eta_k)$ and $dim(\tilde{\varphi}_k(z)) = dim(\bar{\varphi}_k(z)) = (\eta_k \times 1)$ for $k = 1, \dots, p; i = 1, \dots, \eta_k$.

For the following theorem, the linearity in $u$ is not used, then the system is considered:

$$\begin{cases} \dot{z} = Az + \varphi(z,u) \\ y = Cz \end{cases} \tag{3.11}$$

Let $K$ be a matrix $(n \times p, p)$ such that

$$K = \begin{bmatrix} K_1 & & \\ & \ddots & \\ & & K_p \end{bmatrix} \tag{3.12}$$

(with $k_k$ of dimension $n \times 1$), such that for each block $k$, the matrix $A_k - K_k C$ has negative real parts. Then the system is uniformly locally observable, and it exists $T_0 > 0$, such that, for every $T$, such $0 < T < T_0$, the following system constitutes an observer for the system (3.11):

$$\dot{z} = A\hat{z} + \varphi(\hat{\hat{z}}, u) + \Lambda^{-1}(T, \delta) K (y - C\hat{Z}) \tag{3.13}$$

where $\hat{\hat{z}}_{\mu}k = y_k$ ; and $\hat{\hat{z}}_j = \hat{z}_j \neq \mu_k$,

$$\Lambda(T,\delta) = \begin{bmatrix} T^{\delta_1}\Delta_1(T^{\delta_1}) & & \\ & \ddots & \\ & & T^{\delta_p}\Delta_p(T^{\delta_p}) \end{bmatrix} \tag{3.14}$$

with

$$\Delta_k(T) = \begin{bmatrix} T^{\delta_k} & & & & \\ & \ddots & & & \\ & & T^{2\delta_k} & & \\ & & & \ddots & \\ & & & & T^{\eta_k\delta_k} \end{bmatrix} \tag{3.15}$$

Moreover, the standard of the observation error is bounded by an exponential whose decay rate can be chosen arbitrarily large.

**Remarks**:

1. The system

$$\dot{\hat{z}} = A\hat{z} + \varphi(\hat{z},u) + \Lambda^{-1}(T,\delta)K(y - C\hat{Z}) \tag{3.16}$$

is also an observer for the system (3.11). If a change of variable $z = \phi(x)$ is necessary, to return to the old database by $(\hat{x}) = \phi^{-1}(\hat{z})$. By applying this change of coordinates to the previous system, we obtain the observer in the old coordinates.

$$\begin{cases} \dot{\hat{x}}(t) = f(\hat{x}(t)) + \sum_{i=1}^{m} g_i(\hat{x}(t))u_i(t) + [\frac{\partial\phi(x)}{\partial x}]_{\hat{x}}^{-1}\Lambda^{-1}K[y(t) - C\hat{x}(t)] \end{cases} \tag{3.17}$$

2. The observer is written in the new coordinates as a system copy plus a non-linear correction. Implementation requires writing the observer into the original forme.

Therfore the observer becomes:

$$\begin{cases} \dot{\hat{x}}(t) = f(\hat{x}(t)) + \sum_{i=1}^{m} g_i(\hat{x}(t))u_i(t) + [\frac{\partial \phi(x)}{\partial x}]_{\hat{x}}^{-1} \Lambda^{-1} K[y(t) - C\hat{x}(t)] \\ y = Cx \end{cases} \tag{3.18}$$

The term of correction $[\frac{\partial \phi(x)}{\partial x}]_{\hat{x}}^{-1} \Lambda^{-1} K[y(t) - C\hat{x}(t)]$ is explicited then as follows:

$$[\frac{\partial \phi(x)}{\partial x}]_{\hat{x}^{-1}} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{3.19}$$

$$\Lambda^{-1} = \begin{bmatrix} T^{-\delta_1} & 0 & 0 & 0 & 0 \\ 0 & T^{-2\delta_1} & 0 & 0 & 0 \\ 0 & 0 & T^{-\delta_2} & 0 & 0 \\ 0 & 0 & 0 & T^{-2\delta_2} & 0 \\ 0 & 0 & 0 & 0 & T^{-\delta_3} \end{bmatrix} \tag{3.20}$$

The gain $T^{-1}$ must be selected as $0 < T \leq T_0 < 1$. $T_0$ is defined according to different parameters ($\eta^2$, the constant Lipschitz of the function $\varphi(z,u)$ defined by variable change). And the gain $K$ is given by:

$$K = \begin{bmatrix} K_1 & & & & & & & & \\ & \ddots & & & & & & & \\ & & K_2 & & & & & & \\ & & & \ddots & & & & & \\ & & & & K_3 & & & & \\ & & & & & \ddots & & & \\ & & & & & & K_4 & & \\ & & & & & & & \ddots & \\ & & & & & & & & K_5 \end{bmatrix} \tag{3.21}$$

The pair (A,C) is observable, and it is an easy matter to assign eigenvalues to the matrix (*A*-*KC*), that has the companion structure:

$$A - KC = \begin{bmatrix} -K_1 & 1 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ -K_{n-1} & 0 & \dots & 1 \\ -K_n & 0 & \dots & 0 \end{bmatrix} \tag{3.22}$$

If a $n$-pla $\lambda = (\lambda_1, \dots, \lambda_n)$ of eigenvalues has to be assigned, the vector $K(\lambda)$ is the vector that contains the coefficients of the monic polynomial that has $\lambda$ as roots. If the assigned eigenvalues are distinct, matrix (*A*-*KC*) can be diagonalized by a vandermonde matrix :

$$V \equiv V(\lambda) \begin{bmatrix} {\lambda_1}^{n-1} & \dots & \lambda_1 & 1 \\ \vdots & \ddots & \vdots & \vdots \\ -K_{n-1} & \dots & \lambda_n & 1 \end{bmatrix} \tag{3.23}$$

So that

$$V(\lambda)(A - K(\lambda)C)V(\lambda)^{-1} = diag\{\lambda\} = \Lambda \tag{3.24}$$

3. Given a set $\lambda$ of $n$ eigenvalues to be assigned to *A*-*KC*, the gain $K(\lambda)$ is readily computed through the formula:

$$K(\lambda) = -V^{-1}(\lambda)[{\lambda_1}^n \dots {\lambda_n}^n]^T \tag{3.25}$$

which is not difficult to check. It is well known that a vandermonde matrix $V(\lambda)$ is singular if and only if two (or more) eigenvalues in the set $\lambda$ coincide. It is also well known that the smaller is the minimum difference between eigenvalues in $\lambda$, the larger is the norm of $V^1(\lambda)$. For reasons that will be made clear in the following section it is important to choose eigenvalues for matrix $(A - K(\lambda)C)$ keeping bounded the norm of the inverse of the vandermonde matrix $V(\lambda)$. In [102] it is shown that if the $n$ eigenvalues are chosen as $\lambda_j = \lambda_j(w) = -w^j$, for $j = 1, \dots, n$, with $w > 0$, then

$$\lim_{w \to \infty} ||V^{-1}(\lambda(w))|| = 1 \tag{3.26}$$

So, the term of correction of the system is:

$$[\frac{\partial \phi(x)}{\partial x}]_{\hat{x}}^{-1}\Lambda^{-1}K[y(t)-C\hat{x}(t)] = \begin{bmatrix} T^{-\delta_1}K_1(q_1-\hat{q}_1) \\ T^{-2\delta_1}K_2(q_2-\hat{q}_2) \\ T^{-\delta_2}K_3(q_3-\hat{q}_3) \\ T^{-2\delta_2}K_4(q_4-\hat{q}_4) \\ T^{-\delta_3}K_5(q_5-\hat{q}_5) \end{bmatrix} \tag{3.27}$$

Using the system model (3.1), a high-gain observer is developped as explained in section 3.1.2:

$$\begin{cases} \dot{\hat{x}}(t) = f(\hat{x}(t)) + \sum_{i=1}^{m} g_i(\hat{x}(t))u_i(t) + [\frac{\partial \phi(x)}{\partial x}]_{\hat{x}}^{-1}\Lambda^{-1}K[y(t)-C\hat{x}(t)] \\ y = Cx \end{cases} \tag{3.28}$$

The gain $K$ and $T$, show the effectivness of this observer. Thus, the choice of the gain of high-gain observer is based on a compromise between the convergence speed of the observer and insensitivity to measurement noise. The gain K are chosen according to Remark 3, and $T$ between 0 and 1.

### 3.1.3 High Gain Observer and PD controller

In general, an observer is a dynamic system which generate estimations outputs from the current state of the system, by using the previous knowledge of the inputs and outputs of the system [129]. Consider the multi-input multi-output nonlinear system representing in the system (3.1): Assume that the nonlinear system is observable and consider the following coordinate transformation $z(t) = \Phi(x(t))$ where $\Phi(x(t)) = (h(x(t))L_f(h(x(t))...L_f^{n-1}h(x(t)))^T$. $L_f(.)$ represents the Lie derivative of a real function $h(x(t))$ evaluated along $f(x(t))$. By definition, the Lie derivative is
$L_f h(x(t)) = \sum_{i=1}^{n} \frac{\partial h(x(t))}{\partial x_i} f_i(x(t))$.
This coordinate transformation $\phi(x(t))$ determines a diffeomorphism which transforms the system into the following form

$$\begin{cases} \dot{z}(t) = Az(t) + \Psi z(t) + \sum_{i=1}^{m} \phi_i z(t) u_i(t) \\ y(t) = Cz(t) \end{cases} \tag{3.29}$$

This transformation permit to return to the original coordinates, i.e. $x(t) = \phi^{-1}(z(t))$.

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & \dots & 0 & 0 \\ \vdots & \dots & 0 & 0 \\ 0 & \ddots & 0 & 1 \end{bmatrix} z(t) = \begin{bmatrix} 0 \\ \vdots \\ 0 \\ \psi(z(t)) \end{bmatrix} C = \begin{bmatrix} 1 & 0 & \dots & 0 \end{bmatrix} \tag{3.30}$$

The elements of $\phi(z(t))$ are

$$\begin{cases} \phi_1(z(t)) = \phi_1 z_1(t) \\ \phi_2(z(t)) = \phi_2(z_1(t), z_2(t)) \\ \quad\vdots \qquad\qquad \vdots \\ \phi_n(z(t)) = \phi_n(z_1(t), \dots, z_{n-1}(t)) \end{cases} \tag{3.31}$$

For the system given by equation (3.1), an exponential observer can be proposed [265]:

$$\begin{cases} \hat{z}(t) = A\hat{z}(t) + \psi \hat{z}(t) + \sum_{i=1}^{m} \phi(\hat{z}(t)) u_i(t) - S_\theta^{-1} C^T (C\hat{z}(t) - y(t)) \end{cases} \tag{3.32}$$

where $S_\theta$ is a constant $n \times n$ matrix, that is a solution of the Lyapunov equation

$$\theta S_\theta + A^T S_\theta + S_\theta A = C^T C \tag{3.33}$$

where $\theta > 0$ is the tuning parameter of the observer. Considering a second order system the matrix $S_\theta$ is

$$S_\theta = \begin{bmatrix} 1/\theta & -1/\theta^2 & 1/\theta^3 & -1/\theta^4 & 1/\theta^5 \\ -1/\theta^2 & 2/\theta^3 & -3/\theta^4 & 1/\theta^5 & -5/\theta^6 \\ 1/\theta^3 & -3/\theta^4 & 6/\theta^5 & -10/\theta^6 & 15/\theta^7 \\ -1/\theta^4 & 4/\theta^5 & -10/\theta^6 & 20/\theta^7 & -35/\theta^8 \\ 24/\theta^5 & -5/\theta^6 & 15/\theta^7 & -35/\theta^8 & 70/\theta^9 \end{bmatrix} \tag{3.34}$$

The system given by equation (3.1) becomes in the original coordinates:

$$\begin{cases} \dot{\hat{x}}(t) = f(\hat{x}(t)) + \sum_{i=1}^{m} g_i(\hat{x}(t))u_i(t) - [\frac{\partial \phi(\hat{x}(t))}{\partial \hat{x}}]^{-1} S_\theta^{-1} C^T [\hat{y}(t) - y(t)] \\ \hat{y}(t) = C\hat{x}(t) \end{cases} \tag{3.35}$$

where $\frac{\partial \phi(x(t))}{\partial x}$ is the $n \times n$ Jacobian matrix of $\phi(x(t))$, and, $\phi(x(t)) = \phi(x(t))|_{x(t)=\hat{x}(t)}$.

#### 3.1.3.1 PD-based control

To control a non-linear system, one of the practical methods is to design a linear controller based on the linearisation of the system about an operating point. An example of applying this method is a PD control law. In its simplest form, a PD control law can be expressed as:

$$\tau = K_p e + K_d \dot{e} \tag{3.36}$$

Where $K_p$ and $K_d$ are diagonal proportional and derivative gain matrices, respectively, $e = q_d - q$ and $\dot{e} = \dot{q}_d - \dot{q}$ denote the position and velocity error vectors, respectively. Figure (3.1) present the FDI and the controller PD structure.

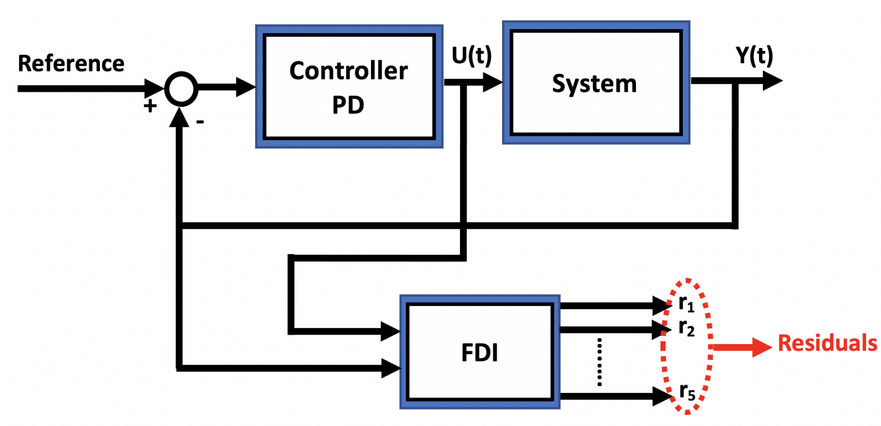



Figure 3.1 – Controller and FDI architecture

$$K_p = \begin{bmatrix} 5.8 & 0 & 0 & 0 & 0 \\ 0 & 5.8 & 0 & 0 & 0 \\ 0 & 0 & 5.8 & 0 & 0 \\ 0 & 0 & 0 & 5.8 & 0 \\ 0 & 0 & 0 & 0 & 5.8 \end{bmatrix} \tag{3.37}$$

$$K_d = \begin{bmatrix} 4.2 & 0 & 0 & 0 & 0 \\ 0 & 4.2 & 0 & 0 & 0 \\ 0 & 0 & 4.2 & 0 & 0 \\ 0 & 0 & 0 & 4.2 & 0 \\ 0 & 0 & 0 & 0 & 4.2 \end{bmatrix} \tag{3.38}$$

The resulting control force $\tau$ is then included in a numerical simulation, along with other forces such as gravity. The stability issue arises when the controller needs to quickly reduce the deviation from the desired position. In this situation, the proportional gain $k_p$ must set to a large value, and the control force can become numerically unstable as the simulation progresses. To improve the stability of a high gain PD controller, we have to sacrifice the efficiency of the simulation by reducing the time step significantly. As a result, PD controllers suffer from undesired coupling between the tracking accuracy and simulation efficiency. Therfore, the system model and the observer are shown in figure (3.2) in order to clarified the structure of residuals generation. The state estimation error $r(t)$ can be calculated as:

$$r(t) = y(t) - \hat{y}(t) \tag{3.39}$$

The residuals are supposed to differ from zero $r(t) \neq 0$ in case of faults and to be zero $r(t) = 0$ when there are no faults on the sensors. So the residuals are evaluated as:

$$r_1 = |q_1 - \hat{q}_1| \tag{3.40}$$

$$r_2 = |q_2 - \hat{q}_2| \tag{3.41}$$

$$r_3 = |q_3 - \hat{q}_3| \tag{3.42}$$

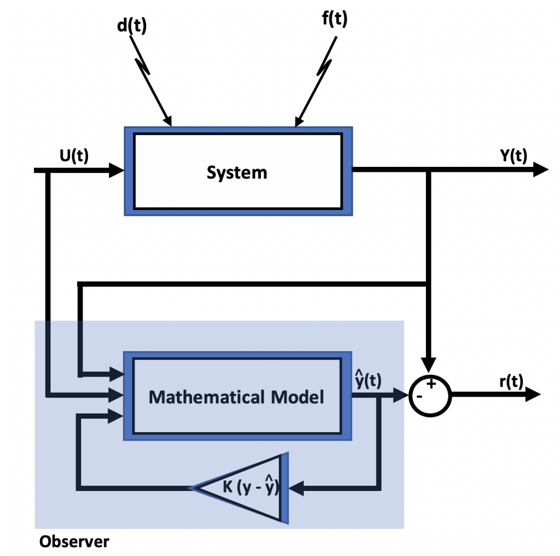



Figure 3.2 – Residual generation

$$r_4 = |q_4 - \hat{q}_4| \tag{3.43}$$

$$r_5 = |q_5 - \hat{q}_5| \tag{3.44}$$

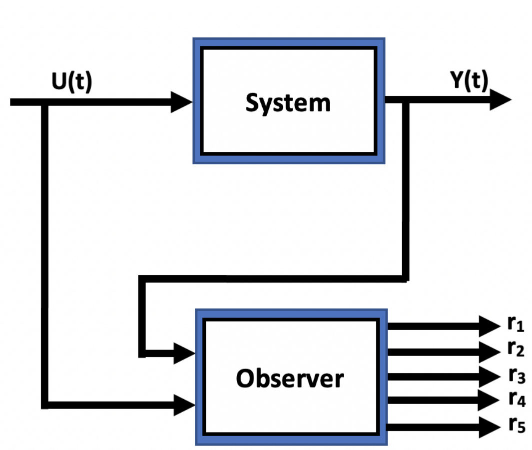



Figure 3.3 – Observer based residual generation

Table (3.1) represents the fault signatures matrix for these residuals. Assuming that simultaneous faults cannot occur, we find that the signatures for each of the failures are quite different.

Table 3.1 – Fault signatures matrix

| $d_i/r_i$ | $r_1$ | $r_2$ | $r_3$ | $r_4$ | $r_5$ |
|---|---|---|---|---|---|
| $d_1$ | 1 | 0 | 0 | 0 | 0 |
| $d_2$ | 0 | 1 | 0 | 0 | 0 |
| $d_3$ | 0 | 0 | 1 | 0 | 0 |
| $d_4$ | 0 | 0 | 0 | 1 | 0 |
| $d_5$ | 0 | 0 | 0 | 0 | 1 |

### 3.1.4 Simulations and results for high gain observer

We simulate the system during $T = 40s$. It is also noted that all faulty signals are additive. The initial condition of the observer are the same of the system.

- A fault $d_1$ is injected on the first joint $(q_1)$ at the time $t = 15s$. Figure (3.4) shows that the residual $r_1$ is different from zero during the presence of fault, and the residuals $(r_2; r_3; r_4; r_5)$ are equal to zero.

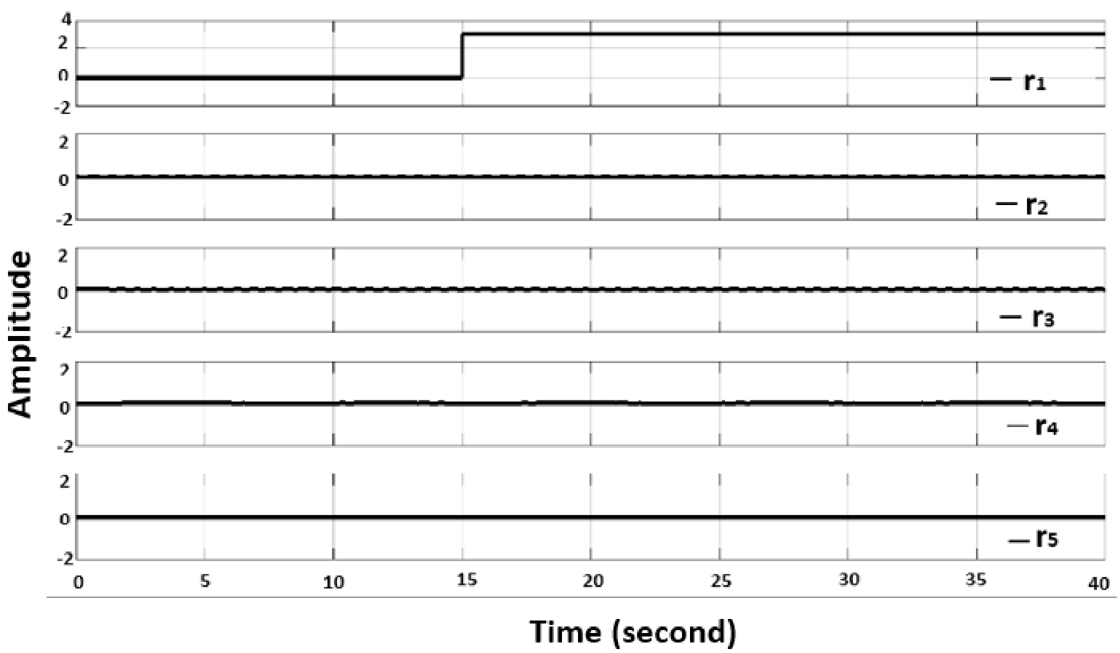



Figure 3.4 – Residuals evolution of the system with fault $d_1$

-The figure (3.5) shows the behavior of the different residuals with the presence of the fault $d_2$ on the second joint $q_2$ at $t = 15s$.

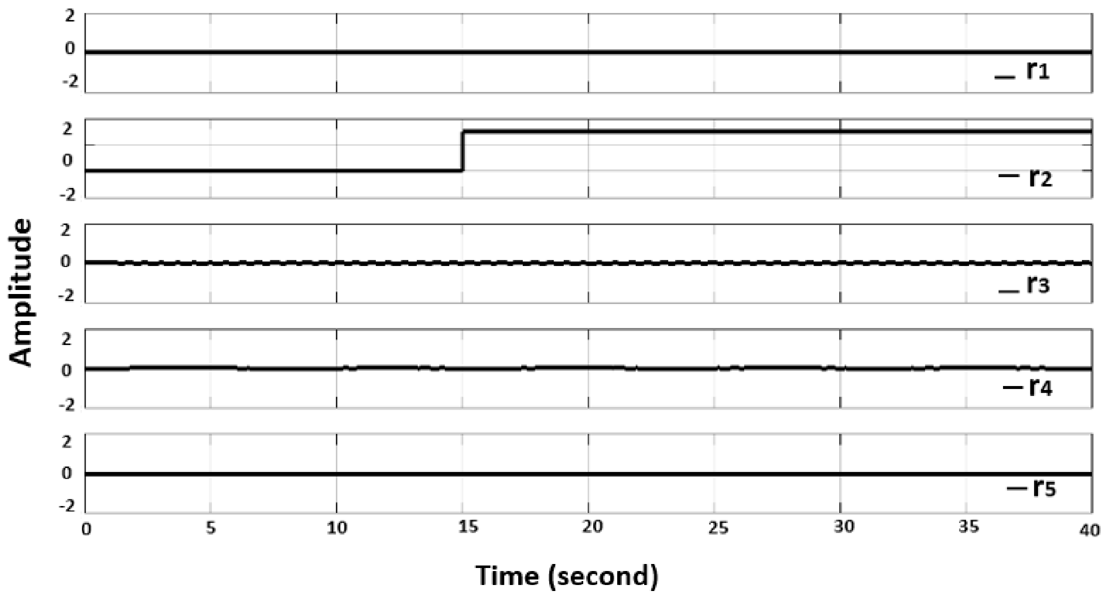



Figure 3.5 – Residuals evolution of the system with fault $d_2$

-A fault $d_3$ is injected on the joint number 3 $(q_3)$ at the instant $t = 15s$. Figure (3.6) shows the evolution of the different residuals. It can be seen that the residuals $(r_1; r_2; r_4; r_5)$ are equal to zero and the residuals $r_3$ is sensitive to the fault.

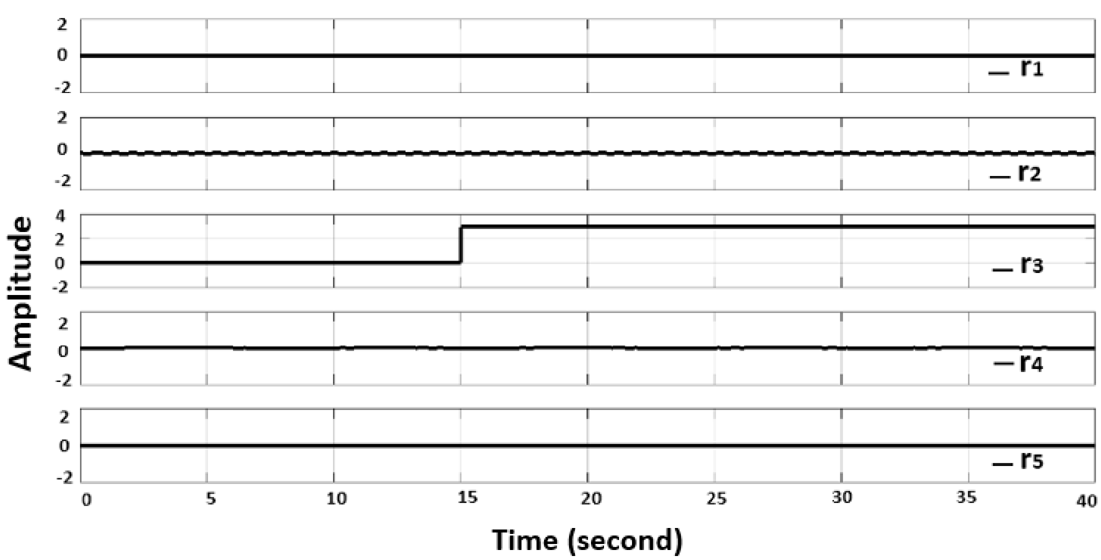



Figure 3.6 – Residuals evolution of the system with fault $d_3$

- A fault $d_4$ injected on the faurth articulation $(q_4)$ at the instant $t = 15s$. Figure (3.7) shows that the residual $r_4$ differ from zero during the failure time and $(r_1;r_2;r_3;r_5)$ are equal to zero.

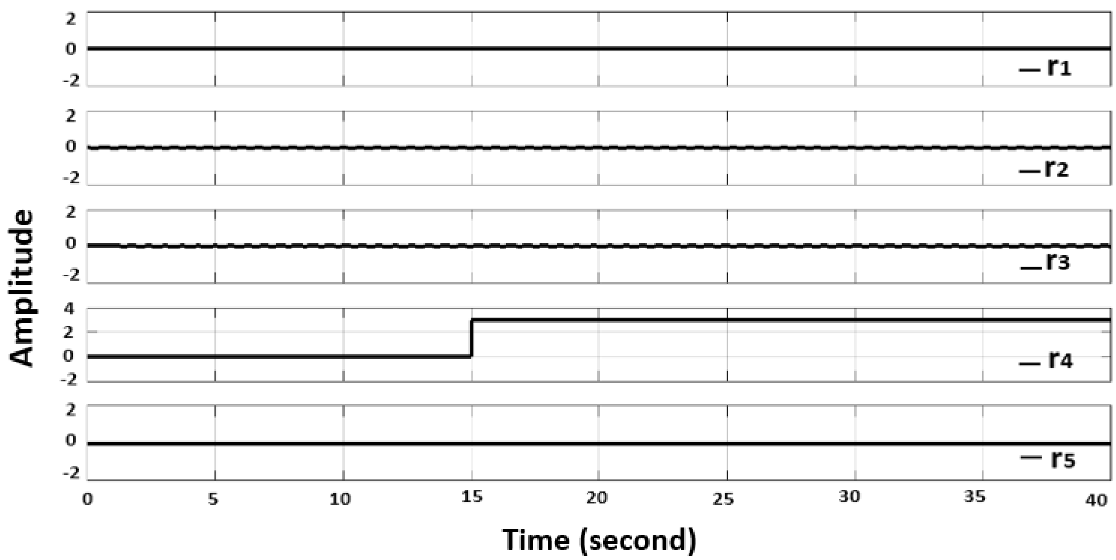



Figure 3.7 – Residuals evolution of the system with fault $d_4$

- A fault $d_5$ is injected on the articulation $(q_5)$ at the time $t = 15s$. Figure (3.8) shows that the residual $r_5$ is sensitive to the fault $d_5$.

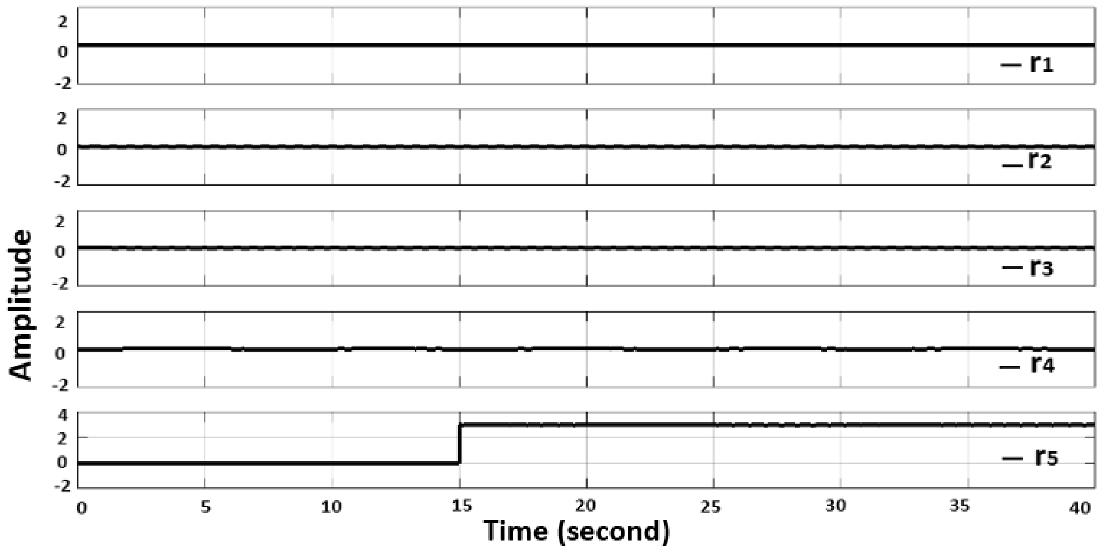



Figure 3.8 – Residuals evolution of the system with fault $d_5$

To sum up, a comparison of the results obtained by the first part of simulation and the second shows that: the first gives a good results, the second part show that when the initials conditions are different to zeros gives also all residuals near of zero.3

#### 3.1.4.1 Simulations and results for high gain observer and PD controller

We simulate the system during $T = 40s$. It is also noted that all faulty signals are additive. The fault is injected at the time $T = 15s$. The initial condition of the system choseen as $q_1 = 0.25rad/s$ ;$q_2 = 0.75rad/s$ ; $q_3 = 0.5rad/s$; $q_4 = 1.25rad/s$; $q_5 = 0.45rad/s$, and for the observer are $q_1 = 0.75rad/s$; $q_2 = 1.25rad/s$; $q_3 = 0.25rad/s$; $q_4 = 0.25rad/s$; $q_5 = 0.75rad/s$.

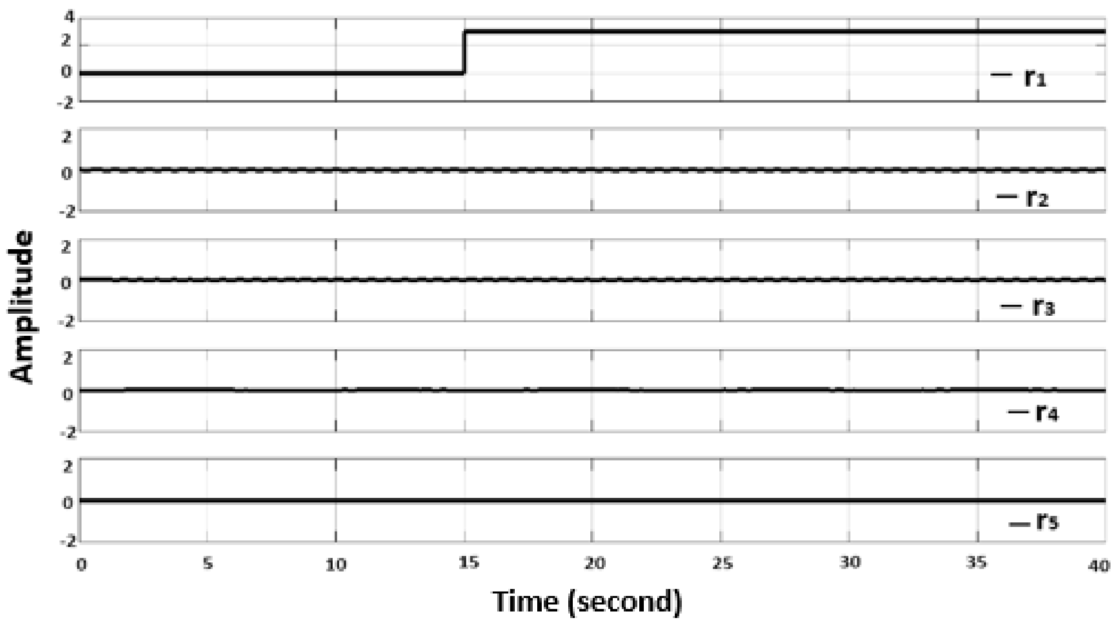



Figure 3.9 – Residuals evolution of the system with fault in the articulation 1.

- A fault $d_1$ is injected on the first joint $(q_1)$ at the time $t = 15s$. Figure (3.9) shows that the residual $r_1$ is different from zero during the presence of fault, and the residuals $(r_2; r_3; r_4; r_5)$ are equal to zero.

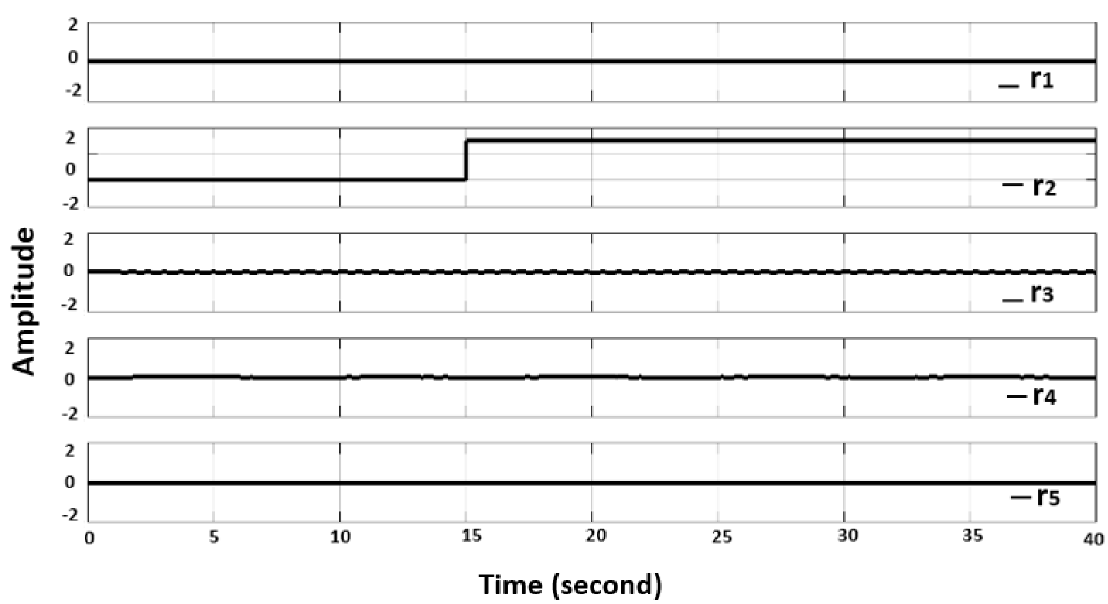



Figure 3.10 – Residuals evolution of the system with fault in the articulation 2.

-A fault $d_2$ is injected on the articulation $(q_2)$ at the time $t = 15s$. Figure (3.10) shows that the residual $r_2$ is sensitive to the fault $d_2$ and $(r_1;r_3;r_4;r_5)$ are equal to zero.

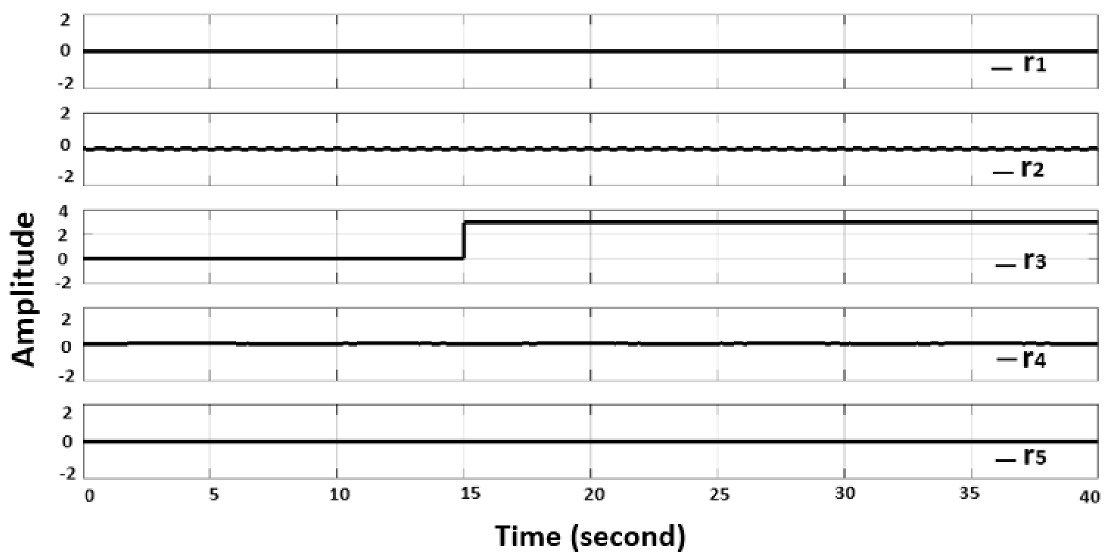



Figure 3.11 – Residuals evolution of the system with fault in the articulation 3.

- A fault $d_3$ injected on the faurth articulation $(q_3)$ at the instant $t = 15s$. Figure (3.11) shows that the residual $r_3$ differ from zero during the failure time and $(r_1;r_2;r_4;r_5)$ are equal to zero.

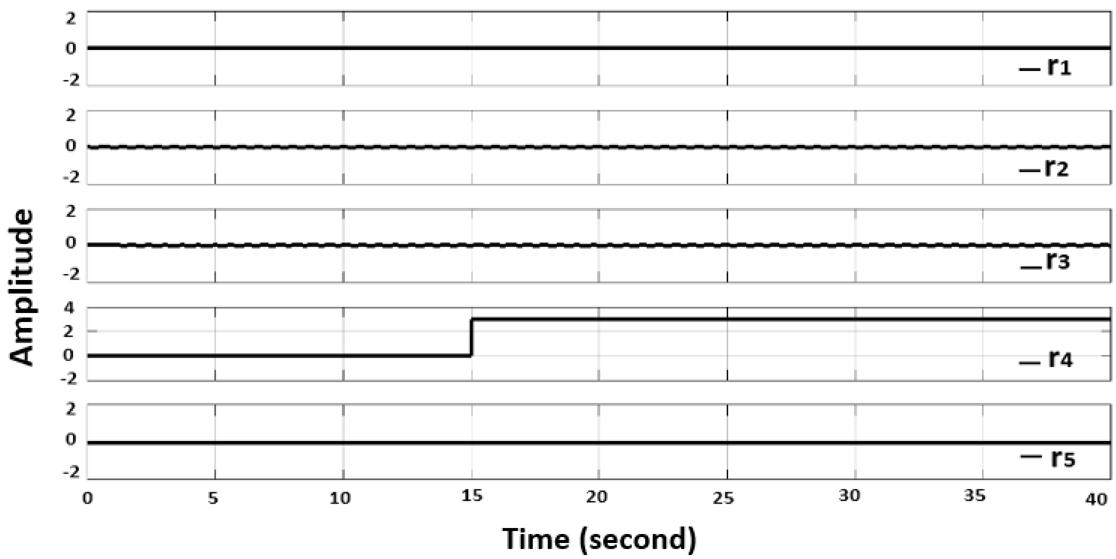



Figure 3.12 – Residuals evolution of the system with fault in the articulation 4.

- A fault $d_4$ is injected on the first joint $(q_4)$ at the time $t = 15s$. Figure (3.12) shows that the residual $r_4$ is different from zero during the presence of fault, and the residuals $(r_1; r_2; r_3; r_4)$ are equal to zero.

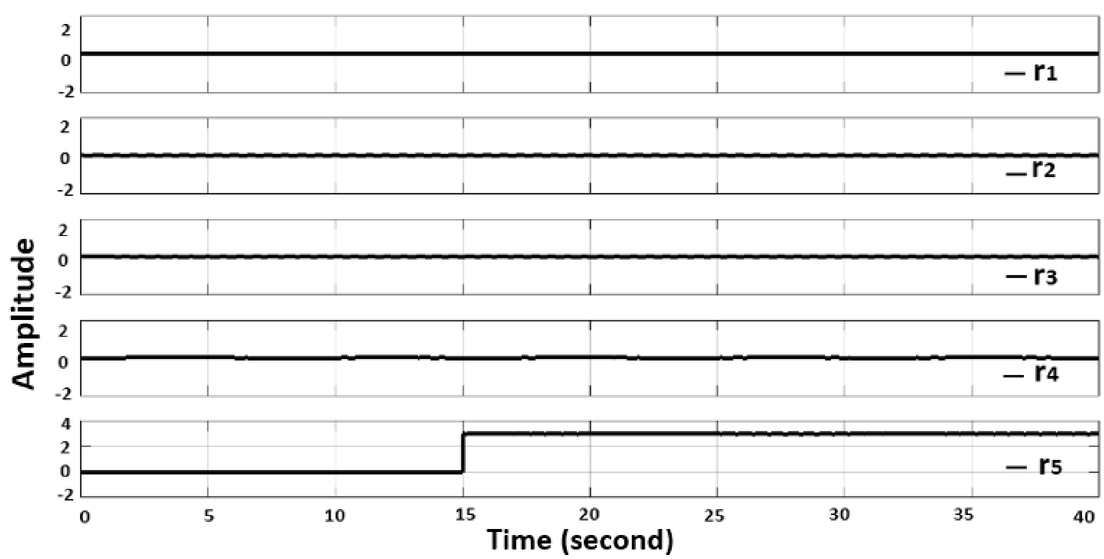



Figure 3.13 – Residuals evolution of the system with fault in the articulation 5.

-At $t = 15s$, the figure (3.13) shows that the residual $r_5$ is sensitive to the fault $d_5$

. Figure (3.13) shows that the residual $r_5$ is different from zero during the presence of fault, and the residuals $(r_1;r_2;r_3;r_4)$ are equal to zero. The simulations gives a good results with a high precision and good performance. Therefore, we can say that the proposed methods gives a good results and it can detect and isolate the sensor faults in a robot manipulator.

## 3.2 Actuator fault detection and isolation for robot manipulator using higher order sliding mode observers

### 3.2.1 The Manipulator Model

The equations of motion of an $n$ Degree of Fredeem (DOF) robot manipulators are described according to the Euler-Lagrange theory, as:

$$\tau = M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) + F(\dot{q}) = M(q)\ddot{q} + n(q,\dot{q}) \tag{3.45}$$

where $q,\dot{q},\ddot{q} \in \mathbf{R}^n$ are the joint position, velocity and acceleration vectors, respectively, $M(q) \in \mathbf{R}^{(n\times n)}$ is the inertia matrix (symmetrical definite positive, thus, $M(q)^{-1}$ always exists), $C(q,\dot{q}) \in \mathbf{R}^{(n\times n)}$ is the centrifugal and Coriolis matrix, $G(q) \in \mathbf{R}^n$ is the gravitational vector, $F(\dot{q}) \in \mathbf{R}^n$ is the vector of viscous friction torque at the joints. Now, introducing the variables $x_1(t) = q(t)$, and $x_2(t) = \dot{q}(t)$, the model 3.45 can be rewritten in state space representation as:

$$\begin{cases} \dot{x}_1(t) = x_2(t) \\ \dot{x}_2(t) = f(\tau(t), x_1(t), x_2(t)) \\ h(t) = x_1(t) \end{cases} \tag{3.46}$$

Where the term $f(\tau(t),x_1(t),x_2(t))$ is obtained after simple algebric manipulation of (3.45), i.e.,

$$f(\tau(t),x_1(t),x_2(t)) = M^{-1}(x_1(t))(\tau(t) - n(x_1(t),x_2(t))) \tag{3.47}$$

As previously mentioned, when faults affect the actuators, the input torque for the mechanical system is different from $\tau(t)$. Then, in case of input faults, (3.45) becomes:

$$\tau(t)+\Delta\tau(t) = M(x_1(t))\dot{x}_2(t)+n(x_1(t),x_2(t)) \tag{3.48}$$

and, as a result, the state space representation is:

$$\begin{cases} \dot{x}_1(t) = x_2(t) \\ \dot{x}_2(t) = f(\tau(t)+\Delta\tau(t),x_1(t),x_2(t)) \\ q(t) = x_1(t) \end{cases} \tag{3.49}$$

where $f(\tau(t)+\Delta\tau(t),x_1(t),x_2(t))$ is analogous to (3.47). In practice, model (3.47) is not exactly known and must be identified. Then, in case of faults, the following relationship holds.

$$\begin{cases} f(\tau(t),x_1(t),x_2(t)) = M^{-1}(x_1(t))(\tau(t)+ \\ \Delta\tau(t)-\hat{n}(x_1(t),x_2(t))-\eta(t)) \end{cases} \tag{3.50}$$

$$\eta(t) = n(x_1(t),x_2(t))-\hat{n}(x_1(t),x_2(t)) \tag{3.51}$$

When $\eta(t)$ is uncertain and $\hat{n}(q,\dot{q})$ is the known part of the model. Yet, by virtue of the particular application considered, $\eta(t)$ can be assumed to be bounded. Obviously, to perform fault diagnosis, one has to rely only on the known part of model (3.47). Indeed, after a suitable identification procedure, such as the one proposed in [232], it is feasible (in absence of faults) to determine only an approximated representation of $f(.)$, i.e.

$$f(\tau(t),x_1(t),x_2(t)) = M^{-1}(x_1(t))(\tau(t)-\hat{n}((x_1(t),x_2(t)) \tag{3.52}$$

in order that the actually usable model is:

$$\begin{cases} \dot{x}_1(t) = x_2(t) \\ \dot{x}_2(t) = \hat{f}(\tau(t), x_1(t), x_2(t)) \\ q(t) = x_1(t) \end{cases} \tag{3.53}$$

By relying on the so-called Unknown Input Observer (UIO) approach [144], efficient estimators of the input torques can be designed [233]. In this work, the UIOs of sliding mode type is proposed in order to detect the actuator faults. The proposed UIOs can be jointly described as a multi-input-multi-state second order sliding mode observers.

### 3.2.2 Observer Design

Let us consider the observer:

$$\begin{cases} \hat{x}_1(t) = \hat{x}_2(t) + z_1(t) \\ \hat{x}_2(t) = \hat{f}(\tau(t), x_1(t), \hat{x}_2(t)) + z_2(t) \end{cases} \tag{3.54}$$

where $\hat{x}_1(t), \hat{x}_2(t) \in \mathbf{R}^n$ are the observer states, and $z(t) = [z_1(t), z_2(t)]^T$ is an auxiliary input signal, which is designed relying on the sliding mode approach, as will be clarified. This signal is introduced so as to permit and guarantee the convergence of the observer states to the actual state of the system. Each component of $z(t)$ is an input law of the observer.

### 3.2.3 Dynamics of the Observer Error

The proposed fault diagnostic scheme requires to steer to zero the signal $e(t) = [e_1(t), e_2(t)]^T \in \mathbf{R}^{2n}$ , the components of which are given by:

$$\begin{cases} e_1(t) = x_1(t) - \hat{x}_1(t) \\ e_2(t) = x_2(t) - \hat{x}_2(t) \end{cases} \tag{3.55}$$

By steering to zero these quantities, it is possible to guarantee that the observer (3.54) gives a good estimation of the unknown input, as it will be shown in the following.
The dynamics of the error variable $e(t)$ is represented by a second order dynamical system:

$$\begin{cases} \dot{e}_1(t) = e_2(t) - z_1(t) \\ \dot{e}_2(t) = f(\tau(t), x_1(t), x_2(t)) - \hat{f}(\tau(t) + \\ \Delta\tau(t), x_1(t), \hat{x}_2(t)) - z_2(t) \end{cases} \tag{3.56}$$

which can be rewritten as:

$$\begin{cases} \dot{e}_1(t) = e_2(t) - z_1(t) \\ \dot{e}_2(t) = M^{-1}(x_1(t)) - (\Delta\tau(t) - \eta(t)) - z_2(t) \end{cases} \tag{3.57}$$

Now, Second Order Sliding Mode approach is studied to design the multi-input-multi-state UIO input law. This approach is the so-called Super-Twisting [231]. The proposal will be depicted in the next subsections.

### 3.2.4 Super-Twisting based Observer

The design of the observer input laws which are the components of $z(t) = [z_1(t), z_2(t)]^T$ using a Super-Twisting based approach (see [231]) is given by:

$$\begin{cases} z_1(t) = \lambda\sqrt{|s'|}sign(s'^{(t)}) \\ z_2(t) = \alpha sing(s'^{(t)}) \end{cases} \tag{3.58}$$

Where $s\prime(t) = e_1(t) = x_1(t) - \hat{x}_1(t)$. It can be proved that a suitable choice of $\lambda$ and $\alpha$ exists such that, starting from any initial condition $[e_1(0), e_2(0)]^T$, the condition:

$$\begin{cases} e_1(t) = 0 \\ e_2(t) = 0 \end{cases} \tag{3.59}$$

is guaranteed in finite time (the proof of this claim can be developed as in [234]). To implement the proposed method, the terms $\alpha$ and $\lambda$ have been chosen after an experimental tuning procedure. Note that the term $z_2(t)$ is a discontinuous signal and, by virtue of the filtering action considered in [84], the second equation of the system (3.57) can be rewritten as:

$$z_{2_{eq}}(t) = M^{-1}(x_2(t))(\Delta\tau(t) - \eta(t)) \tag{3.60}$$

where $z_{2_{eq}}(t)$ is the equivalent input signal corresponding to the discontinuous signal $z_2(t)$. Thus, theoretically, the equivalent input signal is the result of an infinite switching frequency of the discontinuous term $\alpha sing(s\prime(t))$. In fact, the implementation of the observer produces high switching frequency (since, in practice, one can only implement $z_2(t)$ as in equation (3.58) and not $z_{2eq}(t)$) making necessary the application of a filter to obtain useful information from signal $\mathrm{z}_2(t)$. The filter has to eliminate the high frequency components of such a signal. It can be of the form:

$$p\dot{\bar{z}}_{eq}(t) + \bar{z}_{eq}(t) = z_2(t). \tag{3.61}$$

Indeed, in [85], it was shown that :

$$\lim_{p\to 0} \bar{z}_{eq}(t) = z_{2eq}(t) \tag{3.62}$$

Then, by taking a small $p$ it is possible to assume that the equivalent input law (3.60) is similar to the output of the filter.

### 3.2.5 The Considered Fault Scenarios

The occurrences of faults on inputs of a robot manipulator is considered. In this situation, the real torque applied by the actuators is unknown. That is, $\tau \in \mathbf{R}^n$ being the nominal torque calculated by the robot controller, while $\Delta\tau \in \mathbf{R}^n$ being the input fault, the actual torque vector which is the input of the robotic system, can be written as $\tau(t) = \tau(t) + \Delta\tau(t)$ figure (3.14).

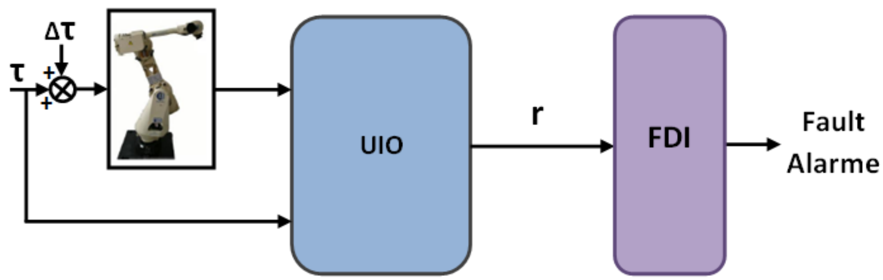



Figure 3.14 – The proposed FDI scheme for actuator faults

### 3.2.6 Residual generation

Error of the state estimation $r(t)$ can be calculated as:

$$r(t) = \tau(t) - \hat{\tau}(t) \tag{3.63}$$

The residuals are supposed to differ from zero in the present of faults ($r(t) \neq 0$) and to be zero when there are no faults on the actuators ($r(t) = 0$). So the residuals are defined as:

$$\begin{cases} r(t) = 0 & if \quad \tau = \hat{\tau} \\ r(t) \neq 0 & if \quad \tau \neq \hat{\tau} \end{cases} \tag{3.64}$$

Table I represents the fault signatures matrix for these residuals. We find that the signatures for each of the failures are quite different.

Table 3.2 – Signature Table for Actuator Fault Isolation

| $d_i/r_i$ | $r_1$ | $r_2$ | $r_3$ | $r_4$ | $r_5$ |
|---|---|---|---|---|---|
| $d_1$ | 1 | 0 | 0 | 0 | 0 |
| $d_2$ | 0 | 1 | 0 | 0 | 0 |
| $d_3$ | 0 | 0 | 1 | 0 | 0 |
| $d_4$ | 0 | 0 | 0 | 1 | 0 |
| $d_5$ | 0 | 0 | 0 | 0 | 1 |

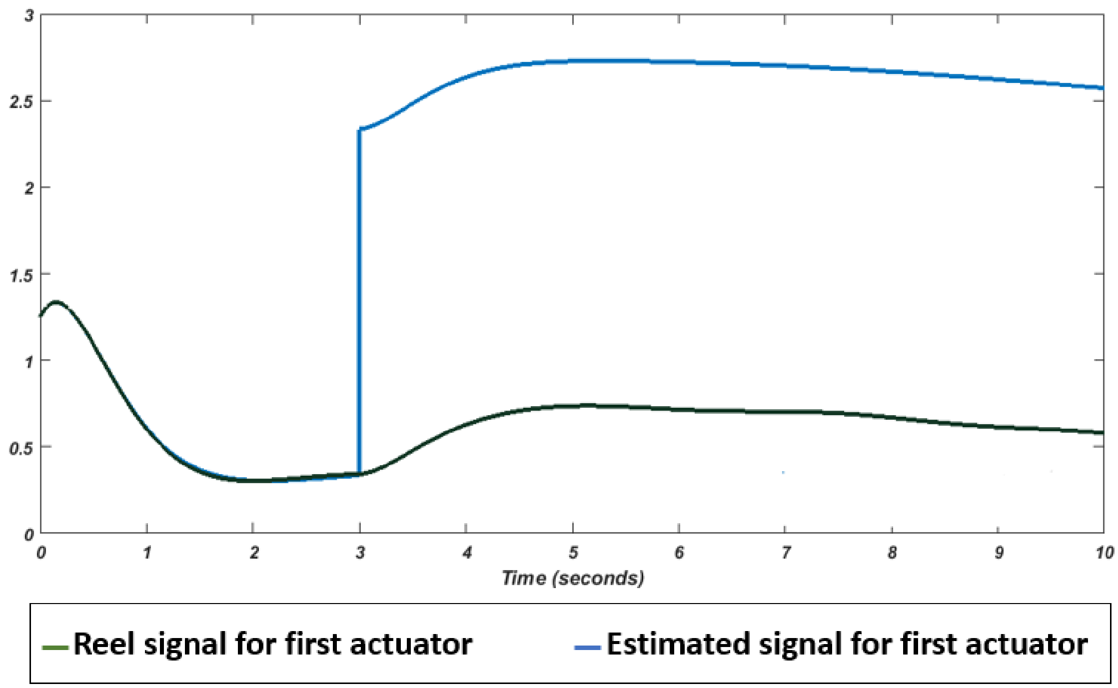
## 3.3 Simulation results

In this part, the performances of the proposed FDI scheme for robot manipulators are verified, by simulating actuator faults. To carry out simulations, the model (4.5) has been simulated together with the observer (4.8) with the input laws (4.17) relevant to the Super-Twisting approach. The presence of actuator faults $\Delta\tau$ is simulated by introducing an abrut fault signal on the different articulation of the robot (joint 1, 2, 3, 4, 5, respectively).

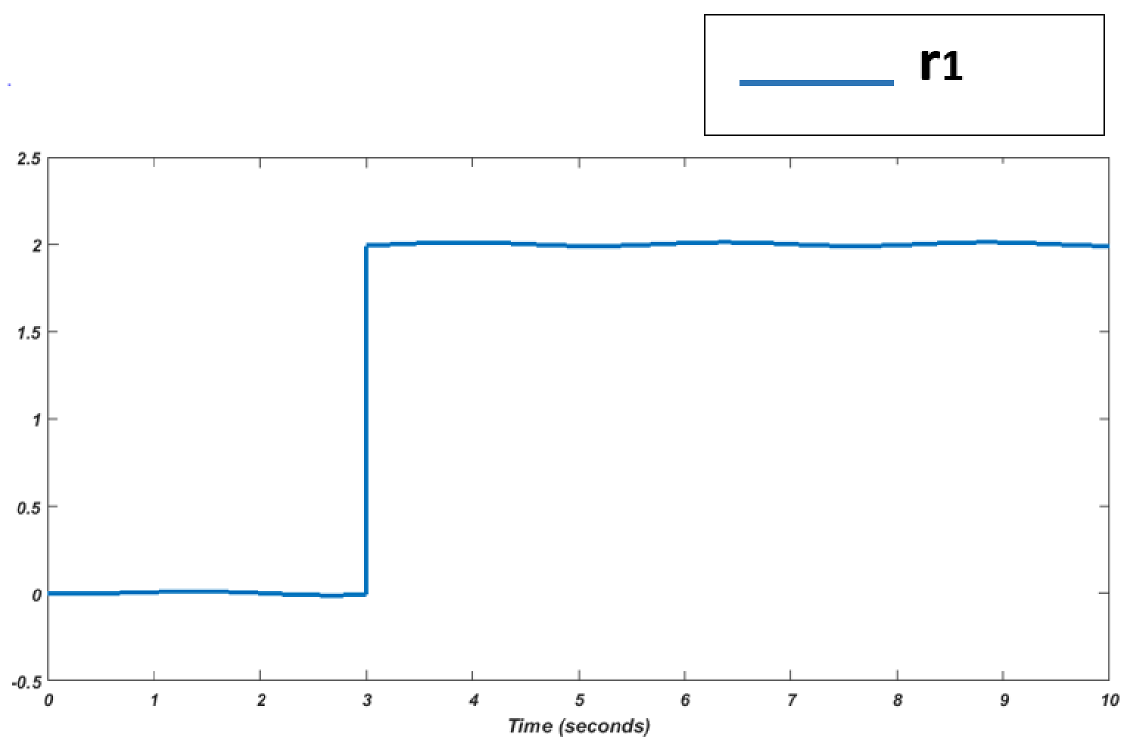
At the time of $t = 3s$ the simulation shows fault detection and isolation for the five articulations of robot manipulators. Detection and isolation of the faults for actuators ($\Delta\tau$ and $\Delta\hat{\tau}$ signals) by using the Super-Twisting input law. Figures (3.15,3.16,3.17,3.18,3.19) presents two signals, one for the actual states and the other for the estimated states. Figures are simulated during the time of $T = 10s$. The kind of fault is "Abrupt". the difference between the two signals gives a residual for each joint of the system.

Figure (b) in figures (3.15,3.16,3.17,3.18,3.19) shows an observation error between the actual states and the estimated states. Residuals for all articulations are different from each other and react according to signature table for actuator fault isolation. The fault is appeared at the time of $t = 3s$.

This methods gives a good results in comparison between the original state and the state estimate, therefore the state estimate converges to the actual state rapidly. So this proposed technique detect and isolate the actuator faults in a robot manipulator.

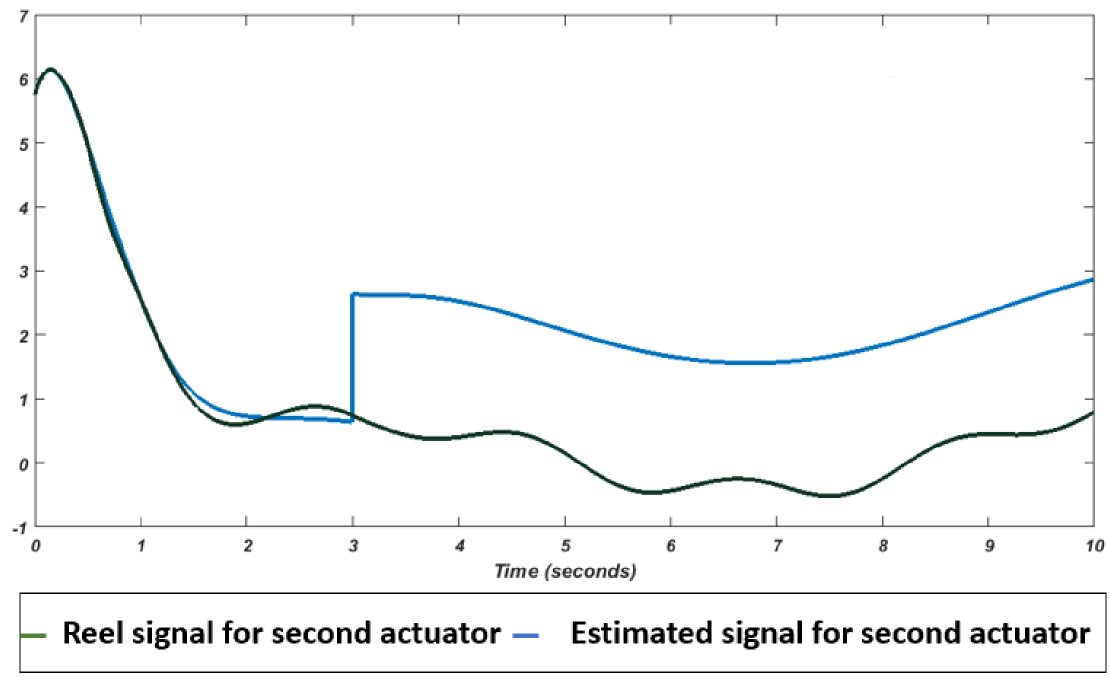



(a) Fault signal reconstruction

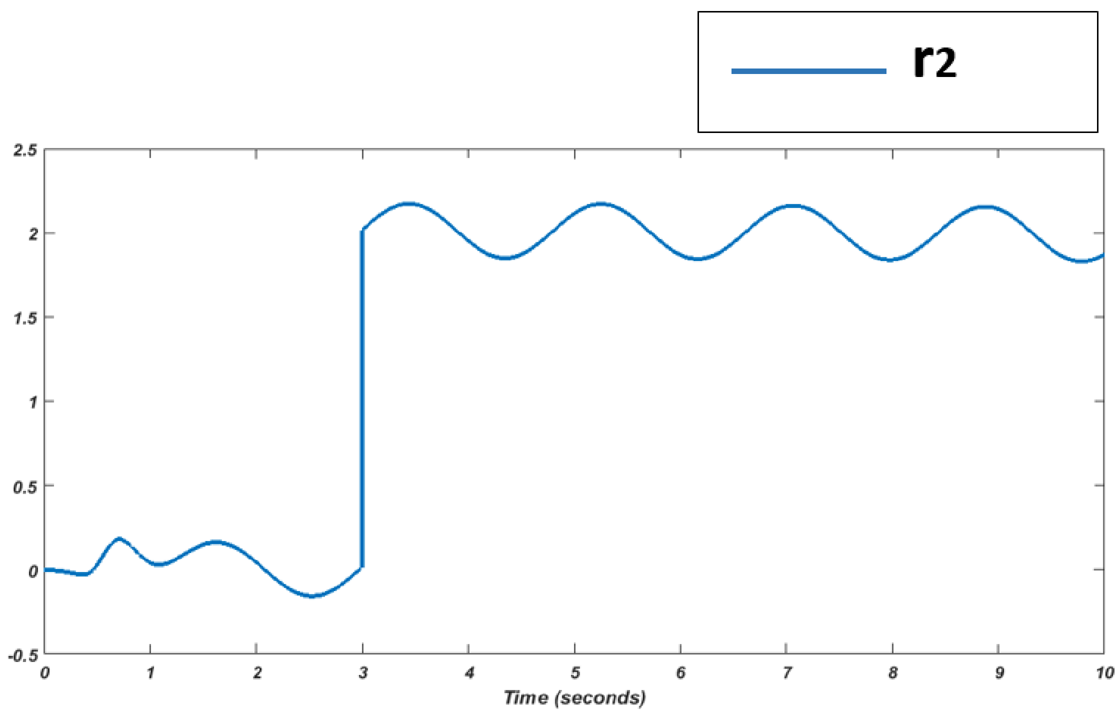



(b) Residual signal for the first actuator

Figure 3.15 – Simulation of FDI on the first actuator ($\Delta\tau$ and $\Delta\hat{\tau}$ signals). Detection and isolation of the faults by using the Super-Twisting input law.

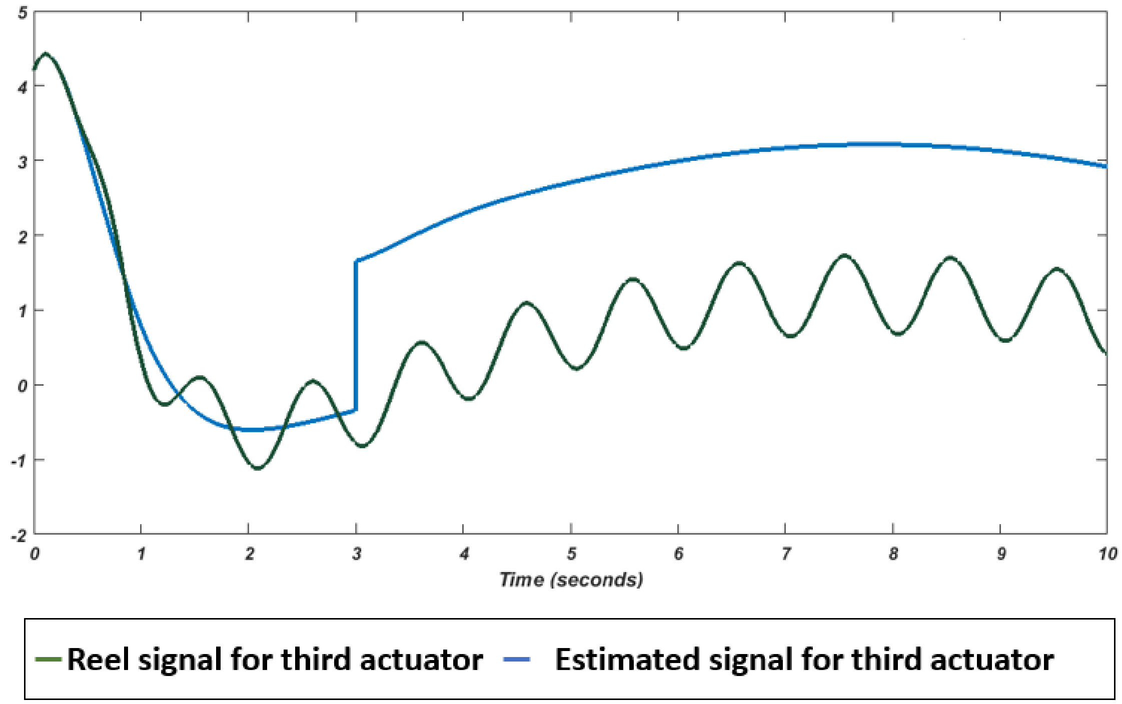



(a) Fault signal reconstruction

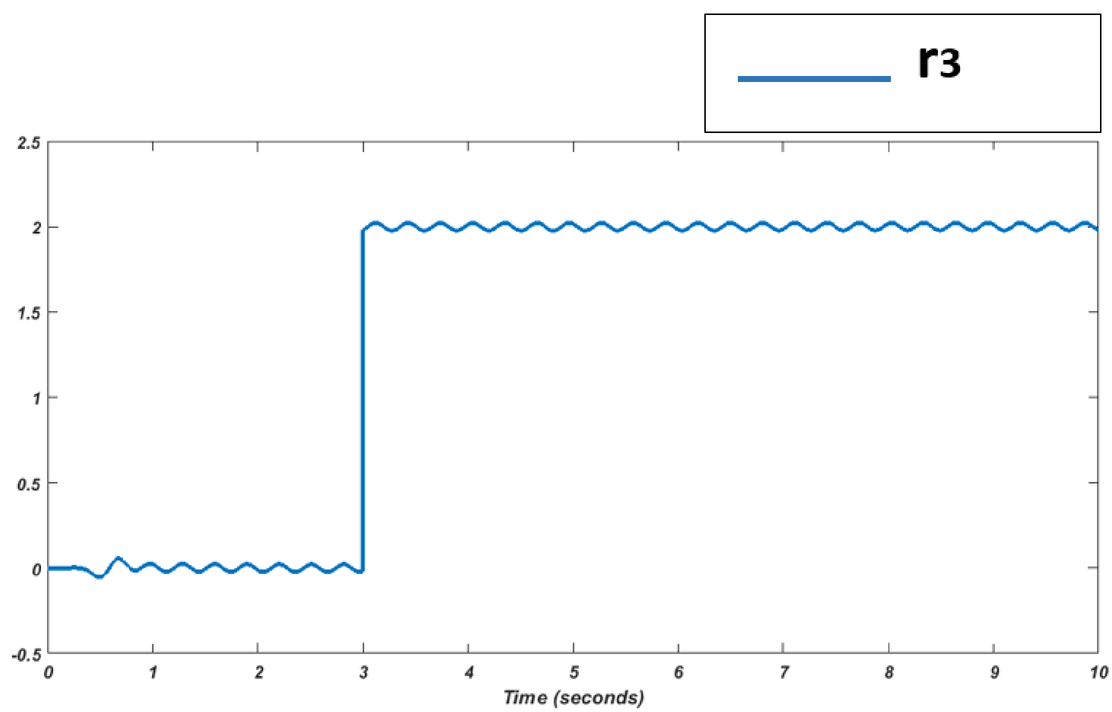



(b) Residual signal for the second actuator

Figure 3.16 – Simulation of FDI on the second actuator ($\Delta\tau$ and $\Delta\hat{\tau}$ signals). Detection and isolation of the faults by using the Super-Twisting input law.

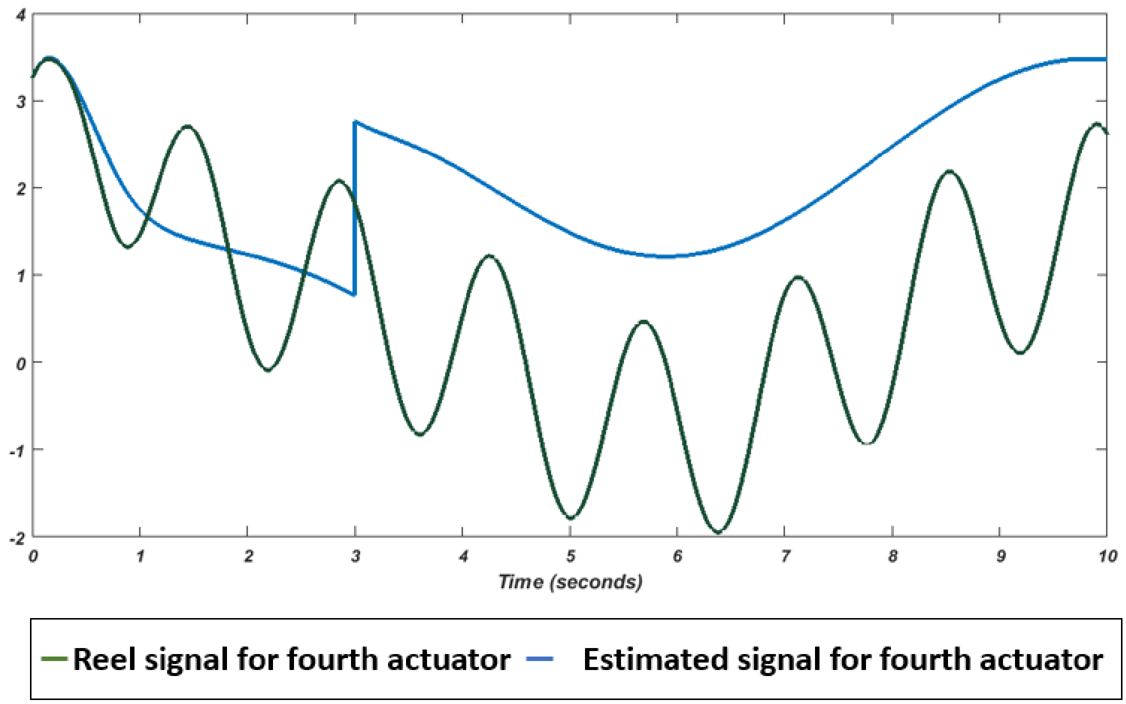



(a) Fault signal reconstruction

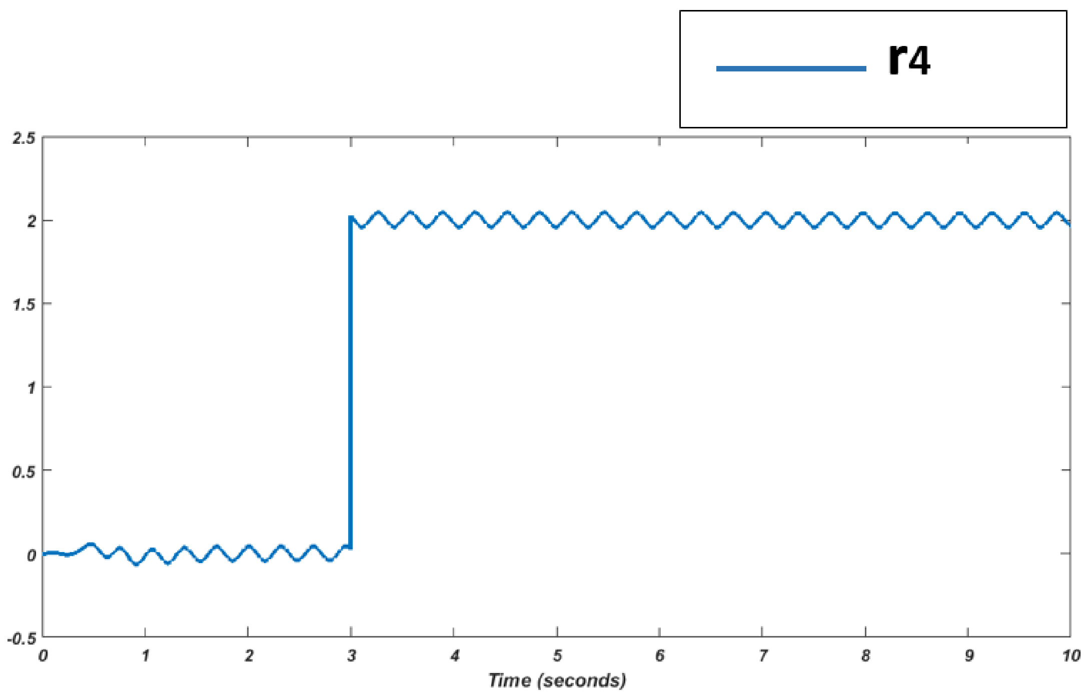



(b) Residual signal for the third actuator

Figure 3.17 – Simulation of FDI on the third actuator ($\Delta\tau$ and $\Delta\hat{\tau}$ signals). Detection and isolation of the faults by using the Super-Twisting input law.

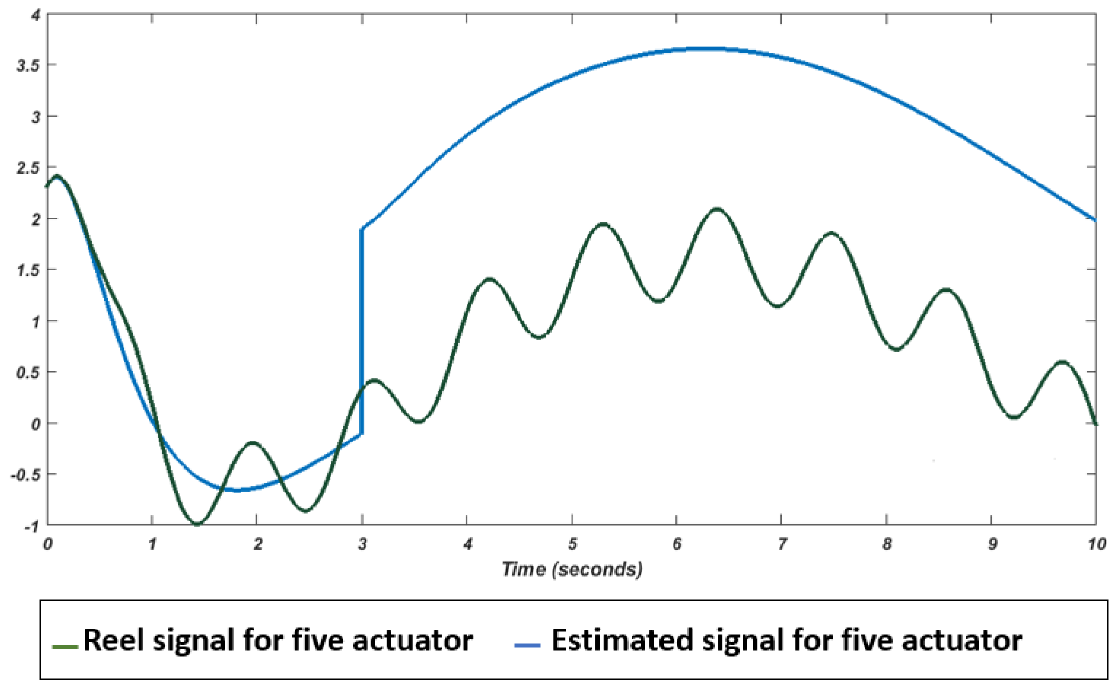



(a) Fault signal reconstruction

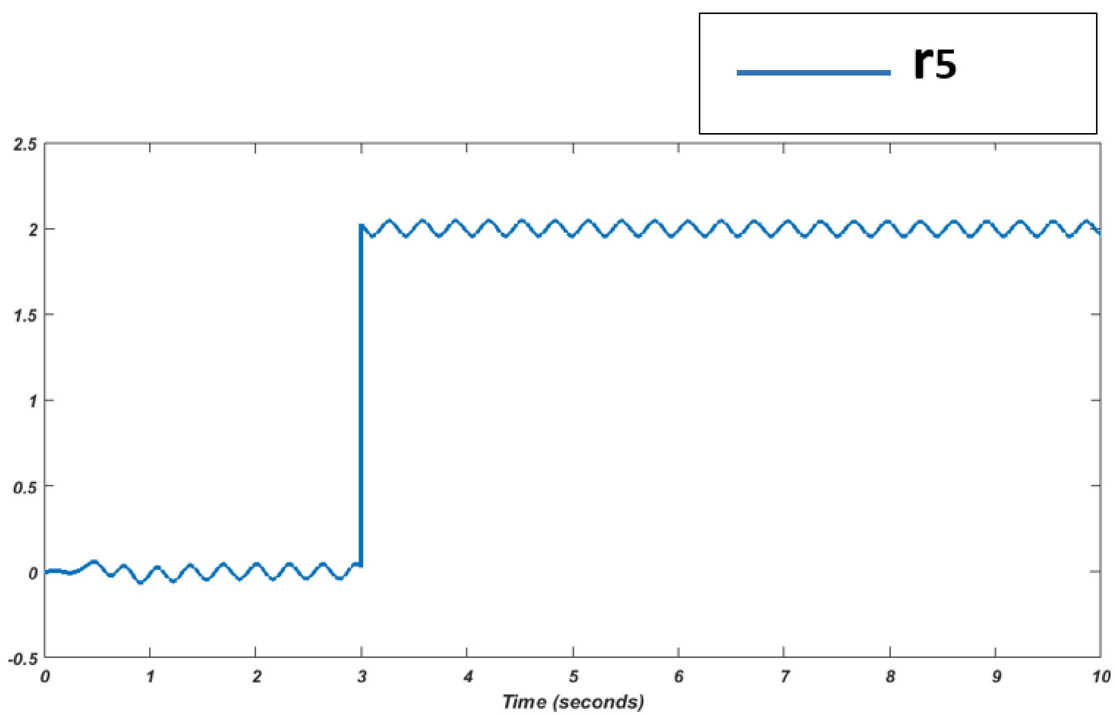



(b) Residual signal for the fourth actuator

Figure 3.18 – Simulation of FDI on the fourth actuator ($\Delta\tau$ and $\Delta\hat{\tau}$ signals). Detection and isolation of the faults by using the Super-Twisting input law.




(a) Fault signal reconstruction




(b) Residual signal for the five actuator

Figure 3.19 – Simulation of FDI on the five actuator ($\Delta\tau$ and $\Delta\hat{\tau}$ signals). Detection and isolation of the faults by using the Super-Twisting input law.

Table 3.3 – Residual generation methods

| *Methods* | *Remarks* | *Reference* |
|---|---|---|
| Unknown Input Observer(UIO) | It cannot isolate simultaneous fault | [266, 267] |
| Dedicated Observer Scheme(DOS). | Sensitive to single faults.It can isolate simultaneous and multiple faults. | [268, 269] |
| Generalized Observer Scheme(GOS). | Sensitive to all faults.It isolate the fault and noise clearly than DOS. | [268, 269] |
| Parity Relations | Residuals are generated without state estimation. It is suitable only for linear systems. | [270] |
| Unscented Kalman Filter(UKF) | Less computation time, less generalization but often leads to false alarm. | [269] |
| Structural Analysis. | Simple and efficient method but result in poor response. | [271] |

## 3.4 Conclusion

In this chapter, based on all methods have their advantages and disadvantages, some of the methods show very effective results such as high gain observer technique but the methodologies used were complicated. The method that indicates a high precision and simple implementation is the sliding mode observer and controller. In the first part, an approach for fault detection and isolation based on the high-gain observer for a class of affine nonlinear systems has been developed. The approach is applied to a robot manipulator to detect and isolate fault sensors, but with two different schemes. In the second part, fault detection and isolation on a robot manipulator have been addressed for fault actuators. The presence of fault detection is performed depending on higher-order sliding mode Unknown Input Observers (UIOs). The observer input laws are designed by the so-called Super-Twisting Second Order Sliding Mode Control (SOSMC). The proposed scheme allows detecting and isolating single and multiple simultaneous faults on the actuators of the robotic system.

# CHAPTER 4

# FAULT TOLERANT CONTROL FOR ROBOT MANIPULATOR

The FTC approaches are developed to improve the safety and reliability of control systems against fault and failures. A control system that can automatically compensate for a fault (and sometimes failures) effect in the system components while maintaining the system stability and the desired level of overall performance is called an FTC system [132, 133, 134, 135].

Generally, based on the dependency on the fault information, FTC systems can be categorized into two main classes: passive FTC and active FTC. Passive FTC is an FTC system that does not rely on faulty information to control the system and is closely related to robust control where a fixed controller is designed to be robust against a predefined fault in the system [132, 136]. In general, redundancy is integrated into the passive fault-tolerant control design to make them resilient against faults [134].

In contrast with passive FTC systems, active FTC systems perform based on the occurred fault in the system. In such control systems, FDI unit is used to find the fault location and measure its size; then, a supervisory controller decides how to modify the control structure and parameters to compensate for the occurred fault in the system. Such modification can be varied from control reconfiguration [137, 138] to managing redundancies [139], and analytical redundancy [140, 141]. Both active and passive approaches use different techniques for the same purpose. However, due to their difference in their design approach, each approach may result in some unique properties.

In this chapter, a high order sliding mode observer (HOSMO) and control (HOSMC) for FDI and FTC are used to compensate both the uncertainties and faults and obtain fast convergence, high accuracy, and less chattering.

## 4.1 Fault Detection and Isolation and Fault-Tolerant Control using High-Order Sliding Mode for Robot Manipulator

### 4.1.1 Mathematical Model of Robot Manipulators

The equations of motion of an n DOF robot manipulators are described according to the Euler-Lagrange theory by:

$$M(q)\ddot{q}+C(q,\dot{q})\dot{q}+G(q)+F(\dot{q})=\tau \tag{4.1}$$

where $q,\dot{q},\ddot{q}\in\mathbf{R}^n$ are the joint position, velocity and acceleration vectors, respectively, $M(q)\in\mathbf{R}^{(n\times n)}$ is the inertia matrix (symmetrical definite positive, thus, $M(q)^{-1}$ always exists), $C(q,\dot{q})\in\mathbf{R}^{(n\times n)}$ is the centrifugal and Coriolis matrix, $G(q)\in\mathbf{R}^n$ is the gravitational vector, $F(\dot{q})\in\mathbf{R}^n$ is the vector of viscous friction torque at the joints.
Introducing new variables $x_1=q$ as the end effector position vector, $x_2=\dot{q}$ as the end effector velocity vector and $x=[q^T,\dot{q}]^T$ as the state vector, the description of the system given in 4.1 can be expressed in state representation form as :

$$\begin{cases}\dot{x}_1=x_2\\ \dot{x}_2=f(x,d,t)+g(x,t)u(t)\end{cases} \tag{4.2}$$

where $x=[x_1^T,x_2^T]^T$ is the state vector with $x_1=[q_1,q_2,q_3,q_4,q_5]^T$ and $x_2=[\dot{q_1},\dot{q_2},\dot{q_3},\dot{q_4},\dot{q_5}]^T$ , and $y=x_1$ is the output vector. $f(x,d,t)$ is the nonlinear dynamics, $g(x,t)$ is the control matrix, $u$ is the control input.
with:

$$f(x,d,t)=-M(q(t))^{-1}[C(q(t),\dot{q}(t))\dot{q}(t)+G(q(t))+F(\dot{q}(t))] \tag{4.3}$$

$$g(x,t)=-M(q(t))^{-1} \tag{4.4}$$

$$u(t)=\tau \tag{4.5}$$

### 4.1.2 Problem statements

Consider the robot dynamics described by

$$\ddot{q} = M(q)^{-1}(\tau - C(q,\dot{q}\dot{q}) - F(\dot{q}) - G(q)) - \tau_d) + \beta(t - T_f)\phi(q,\dot{q},\tau) \tag{4.6}$$

where $q,\dot{q},\ddot{q} \in \mathbf{R}^n$ are the joint position, velocity and acceleration vectors, respectively, $M(q) \in \mathbf{R}^{(n\times n)}$ is the inertia matrix (symmetrical definite positive, thus, $M(q)^{-1}$ always exists), $C(q,\dot{q}) \in \mathbf{R}^{(n\times n)}$ is the centrifugal and Coriolis matrix, $G(q) \in \mathbf{R}^n$ is the gravitational vector, $F(\dot{q}) \in \mathbf{R}^n$ is the vector of viscous friction torque at the joint,$\phi(q,\dot{q},\tau) \in \mathbf{R}^n$is a vector of sensors, $\beta(t-T_f) \in \mathbf{R}^n$ represents the time profile of the faults, and $T_f$ is the time of occurrence of the faults, that is;

$$\beta_i(t-T_f) = \begin{cases} 0 & if \quad t < T_f \\ 1 - e^{-\varphi}(t-T_f) & if \quad t \geq T_f \end{cases} \tag{4.7}$$

where $\varphi_i > 0$ represents the unknown fault evolution rate. A small value of $\varphi_i$ characterizes a slowly developing fault, also called an incipient fault. For a large value of $\varphi_i$, the profile of $\beta_i$ approaches a step function that models abrupt faults. When $\varphi_i \to \infty$, $\beta_i$ becomes a step function so that the incipient fault becomes an abrupt fault. To simplify the subsequent design and analysis, (4.6) can be rewritten as

$$\ddot{q} = M(q)^{-1}(\tau - H(q,\dot{q})) - \Delta(q,\dot{q},t) + \beta(t-T_f)\phi(q,\dot{q},\tau) \tag{4.8}$$

where $H(q,\dot{q}) = C(q,\dot{q}) + G(q)$ and $\Delta(q,\dot{q},t) = M^{-1}(q)(F(\dot{q})\tau_d)$ represents the modeling uncertainty in the dynamic model of robot manipulators.

In this work, we studied a super twisting third order sliding mode (STW-TOSM) observer to estimate the system states and get the residual generation signals in order to have the fault information for using an active FTC approach by utilizing a super twisting second order sliding mode (STW-SOSM) controller to accommodate the effects of uncertainties and faults so as to stabilize and increase the tracking performance of the robot

manipulator in the case of the fault free and the faulty operation modes. The principal idea of the design can be shown in figure (4.1). Here, the following assumptions are made.
Assumption 1. The modeling uncertainty is bounded such that

$$||M^{-1}(q)(F(\dot{q})+\tau_d)|| = \Delta(q,\dot{q},t) \leq \bar{\Delta}, \tag{4.9}$$

where $\bar{\Delta}$ is a known constant.
Assumption 2. The unknown fault function is bounded as

$$||\phi(q,\dot{q},\tau)|| < \bar{\phi}, \tag{4.10}$$

where $\bar{\phi}$ is a known constant.

## 4.2 Sensors fault detection strategy: GOS scheme with sliding mode observers and residual generation.

### 4.2.1 Sensors fault detection strategy

To perform the detection of sensor faults, $n$ observers are used, one for each sensor. This strategy, called Generalized Observer Scheme (GOS). The inputs of the $i^{th}$ GOS observer used sensor measurements coming from the $i^{th}$ sensor, and utilized the control law figure (4.1).

#### 4.2.1.1 Residual generation

The state estimation error $r(t)$ can be calculated as:

$$r(t) = y(t) - \hat{y}(t) \tag{4.11}$$

The residuals are supposed to differ from zero in the present of faults ($r(t) \neq 0$) and to be zero when there are no faults on the sensors ($r(t) = 0$). So the residuals are defined

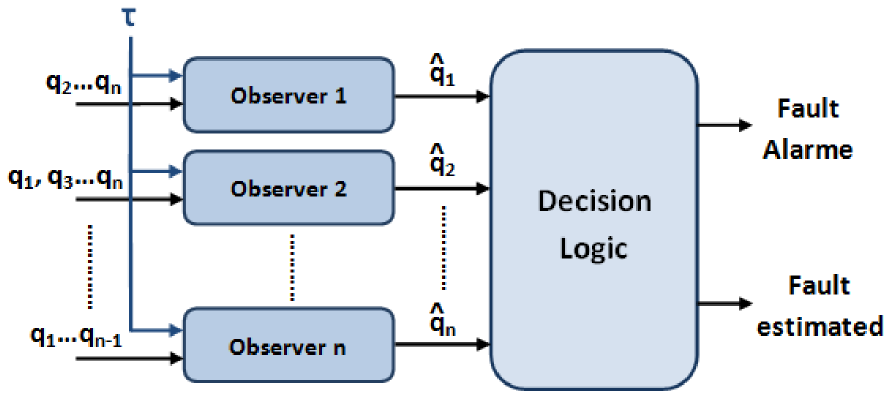



Figure 4.1 – Generalized observer scheme (GOS) for a sensors system

as:

$$r_1 = |q_1 - \hat{q}_1| \tag{4.12}$$

$$r_2 = |q_2 - \hat{q}_2| \tag{4.13}$$

$$r_3 = |q_3 - \hat{q}_3| \tag{4.14}$$

$$r_4 = |q_4 - \hat{q}_4| \tag{4.15}$$

$$r_5 = |q_5 - \hat{q}_5| \tag{4.16}$$

Table (4.1) represents the fault signatures matrix for these residuals. We find that the signatures for each of the failures are quite different.

Table 4.1 – Signature Table for Sensor Fault Isolation

| $d_i/r_i$ | $r_1$ | $r_2$ | $r_3$ | $r_4$ | $r_5$ |
|---|---|---|---|---|---|
| $d_1$ | 0 | 1 | 1 | 1 | 1 |
| $d_2$ | 1 | 0 | 1 | 1 | 1 |
| $d_3$ | 1 | 1 | 0 | 1 | 1 |
| $d_4$ | 1 | 1 | 1 | 0 | 1 |
| $d_5$ | 1 | 1 | 1 | 1 | 0 |

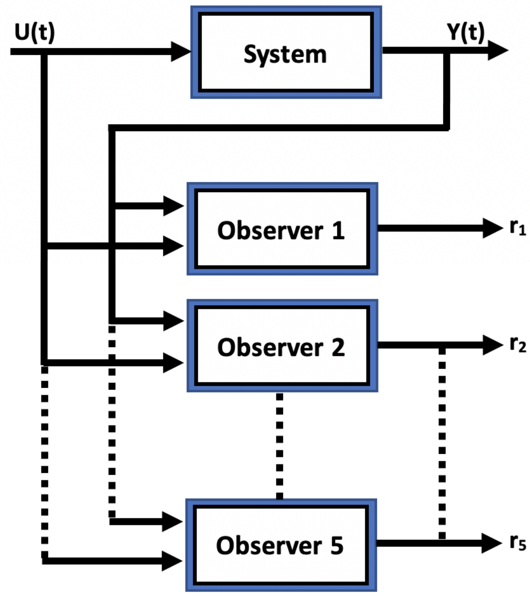



Figure 4.2 – Observer based residual generation

## 4.3 Fault Detection and Isolation Scheme Based on a Super-Twisting Third-Order Sliding Mode Observer.

In this section, the observer scheme that is used for both state observer and fault diagnosis based on STW-TOSM observer is designed. With $x_1 = q \in \mathbf{R}^n$ and $x_2 = \dot{q} \in \mathbf{R}^n$, the robot dynamics expressed in (4.6) can be written in state-space form as

$$\begin{aligned} \dot{x}_1 &= x_2, \\ \dot{x}_2 &= f(x_1, x_2, \tau) + \Delta(x_1, x_2, t) + \beta(t - T_f)\phi(x_1, x_2, \tau), \\ y &= x_1, \end{aligned} \tag{4.17}$$

where $f(x_1, x_2, \tau) = M^{-1}(q)[\tau - C(q, \dot{q})\dot{q} - G(q)]$. We consider an STW-TOSM observer with the following form [272, 273]:

$$\begin{aligned} \dot{\hat{x}}_1 &= \hat{x}_2 + \alpha_2 ||x_1 - \hat{x}_1||^{2/3} sign(x_1 - \hat{x}_1) \\ \dot{\hat{x}}_2 &= f(x_1, \hat{x}_2, \tau) + \alpha_1 ||\dot{\hat{x}}_1 - \hat{x}_2||^{1/2} sign(\dot{\hat{x}}_1 - \hat{x}_2) + \hat{z}_{eq} \\ \dot{\hat{z}}_{eq} &= \alpha_0 sign(\dot{\hat{x}}_1 - \hat{x}_2), \end{aligned} \tag{4.18}$$

where $\alpha_i$ the sliding mode gain to be desingned. Substituting (4.17) into (4.18), the state estimation error is defined as

$$\begin{aligned}
&\dot{\hat{x}}_1 = \tilde{x}_2 - \alpha_2 ||x_1 - \hat{x}_1||^{2/3} sign(x_1 - \hat{x}_1) \\
&\dot{\hat{x}}_2 = d(x_1, \hat{x}_2, \tilde{x}_2) + \Delta(x_1, x_2, t) + \phi(x_1, x_2, \tau) \\
&- \alpha_1 ||\dot{\hat{x}}_1 - \hat{x}_2||^{1/2} sign(\dot{\hat{x}}_1 - \hat{x}_2) - \hat{z}_{eq} \\
&\dot{\hat{z}}_{eq} = \alpha_0 sign(\dot{\hat{x}}_1 - \hat{x}_2),
\end{aligned} \tag{4.19}$$

where $\tilde{x}_i = x_i - \hat{x}_i (i = 1,2)$ and $d(x_1, \hat{x}_2, \tilde{x}_2) = f(x_1, x_2, \tau) - f(x_1, \hat{x}_2, \tau)$. If we defined $F(x_1, x_2, \hat{x}_2, \tau) = d(x_1, \hat{x}_2, \tilde{x}_2) + \Delta(x_1, x_2, t) + \phi(x_1, x_2, \tau)$, based on assumptions 1 and 2, there exists a constant $f^+$ such that

$$F(x_1, x_2, \hat{x}_2, \tau) < f^+ \tag{4.20}$$

Based on the analysis in [272], the sliding gains can be selected as $\alpha_0 = 1.1 f^+, \alpha_1 = 1.5(f^+)^{1/2}, \alpha_2 = 1.9(f^+)^{1/3}$ to guarantee the stability and convergence. After convergence of the differentiator, the estimation states $(\hat{x}_1, \hat{x}_2)$ converge to the true state $(x_1, x_2)$, and the following equalities are satisfied:

$$\Delta(x_1, x_2, t) + \phi(x_1, x_2, \tau) - \alpha_1 ||\dot{\hat{x}}_1 - \hat{x}_2||^{1/2} sign(\dot{\hat{x}}_1 - \hat{x}_2) - \hat{z}_{eq} = 0. \tag{4.21}$$

When the differentiator converges to zero, the third term of (4.21) is equal to zero. The uncertainties and faults can then be reconstructed as

$$\hat{z}_{eq} = \Delta(x_1, x_2, t) + \phi(x_1, x_2, \tau) \tag{4.22}$$

In (4.18) and (4.22), $\hat{z}_{eq}$ is a continuous term and thus a low-pass filter is not needed to obtain the equivalent output injection. Consequently, there are a theoretical estimation of the unknown inputs (uncertainties and faults) without filtration. This is very useful in designing the active FTC, which requires accurate fault estimation.

#### 4.3.0.1 Fault Detection and Isolation Decision.

The proposed STW-TOSM observer is able to detect system faults in the presence of uncertainties. The fault diagnosis system must be robust against system uncertainties but must also be sensitive to any fault. In this paper, the obtained EOI of the STW-TOSM in 4.18 is used as a residual to detect and isolate faults. According to (4.7), $\phi(q, \dot{q}, \tau) = 0$ when $t < T_f$, the system is in normal operation. Then, from 4.18, $\hat{z}_{eq} = \Delta(q, \dot{q}, t)$, and from Assumption 2 we have

$$\hat{z}_{eq} = \Delta(x_1, x_2, t) \leq \bar{\Delta} = z_{th}. \tag{4.23}$$

The threshold is chosen such that the residual can clearly distinguish between normal operation and fault operation. Because the residual $\hat{z}_e q$ is always smaller than $z_{th}$ in normal operation, $z_t h$ is chosen as the threshold [110]. When a fault occurs, the residual $\hat{z}_{eq} = \Delta(x_1, x_2, t) + \phi(q, \dot{q}, \tau) > z_{th}$, and the fault is declared. Thus, fault is detected and isolated whenever the residual $(\hat{z}_e q)$ overshoots its corresponding threshold $(z_{th})$.

## 4.4 Sliding mode fault tolerant control

The proposed robust active FTC schemes based on SMC and STW-SOSM are designed using the STW-TOSM observer-based fault detection qnd isolation. The goal of the FDI is get fault information obtained fault information and utilized for compensating the fault effect of robot manipulator system. Then, the SM control technique is replacing by STW-SOSM scheme to achieve and guarantee the stability of the system, to compensate the error, to ensure finite time convergence, to obtain higher accuracy and reduce the chattering.

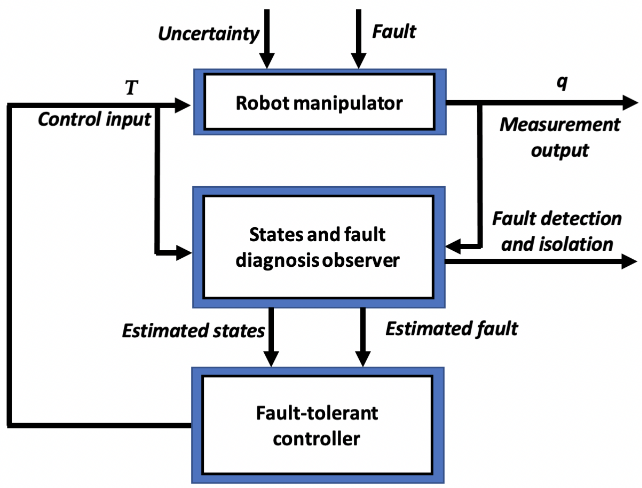



Figure 4.3 – Block diagram for fault diagnosis and fault-tolerant control.

### 4.4.1 Active FTC Based on Conventional Sliding Mode Control and Fault Estimation.

According to the design procedure illustrated in figure (4.3), the proposed active FTC is designe as

$$u = u_{eq} + u_c + u_s \tag{4.24}$$

where $u_{eq}$ is designed as in (4.27) and is used to control the nominal system.
$u_c$ is the compensated uncertainty and fault based on the obtained EOI of the STW-TOSM observer.
$u_s$ is used to compensate for the STW-TOSM compensation error.
These parameters are designed such that

$$u_c = -M(x_1)\hat{z}_{eq} \tag{4.25}$$

and the parameter $u_s$ is designed such that

$$u_s = -M(x_1)\upsilon sign(s) \tag{4.26}$$

$$u_{eq} = M(x_1)(\ddot{x}_d - \lambda(\hat{x}_2 - \dot{x}_d) - g(x_1, \hat{x}_2)) \tag{4.27}$$

where $\upsilon$ is sliding mode gain. The derivative of the sliding surface is now obtained under the control input expressed in (4.24) as:

$$\begin{aligned}
\dot{s} &= \ddot{e} + \lambda \dot{e} \\
&= M^{-1}(x_1)(u_e q + u_c + u_s) + g(x_1, x_2) + \Delta(x_1, x_2, t) + \\
&+ \phi(x_1, x_2, u) - \ddot{x_d} + \lambda(x_2 - \dot{x_d}) \\
&= M^{-1}(x_1)(u_s) - \hat{z}_{eq} + \Delta(x_1, x_2, t) + \phi(x_1, x_2, u) \\
&= M^{-1}(x_1)(u_s) - (\hat{\Delta}(x_1, x_2, t) + \hat{\phi}(x_1, x_2, u)) + \\
&+ \Delta(x_1, x_2, t) + \phi(x_1, x_2, u) \\
&= -\upsilon sign(s) + \varepsilon_1 + \varepsilon_2
\end{aligned} \tag{4.28}$$

where $\hat{\Delta}(x_1, x_2, t)$ and $\hat{\phi}(x_1, x_2, u)$ are the uncertainty and fault estimations provided by the EOI of the STW-TOSM observer, respectively, $\varepsilon_1 = \Delta(x_1, x_2, t) - \hat{\Delta}(x_1, x_2, t)$ is the uncertainty estimation error, and $\varepsilon_2 = \phi(x_1, x_2, \tau) - \hat{\phi}(x_1, x_2, \tau)$ is the fault estimation error. Due to the ability of the STW-TOSM observer to be robust toward uncertainties and faults, the estimation errors are bounded such that $\varepsilon_1 \le \bar{\varepsilon}_1$ and $\varepsilon_2 \le \bar{\varepsilon}_2$.

### 4.4.2 Active FTC Based on a Super-Twisting Second-Order Sliding Mode Controller and Fault Estimation.

Although the active FTC scheme in (4.24) can reduce the chattering due to the reduced sliding gain in the switching term, the use of the discontinuous sign function of the conventional SMC still generates chattering. To remove the chattering and to obtain higher accuracy, a STW-SOSM controller is designed to replace the conventional SMC. Because the super-twisting algorithm contains a discontinuous function under the integral, the chattering is not eliminated but is greatly attenuated.

Starting from (4.28) with $u_{eq}$ and $u_c$ given in (4.27) and (4.25), respectively, the derivative of the sliding surface $\dot{s}$ can be rewritten as

$$\dot{s} = M^{-1}(x_1) u_s + \rho(t, x_1, x_2), \tag{4.29}$$

where $u_s$, the control input, is now designed based on the STW-SOSM controller and $\rho(t, x_1, x_2) = \varepsilon_1 + \varepsilon_2 \leq \bar{\varepsilon_1} + \bar{\varepsilon_2} = \bar{\varepsilon}$ is assumed to be an unknown perturbation bounded term. At this point, the stability of the STW-SOSM controller can be proposed as follows [113]:

$$\begin{aligned} u_s &= -M(x_1)u_{stw-sosm}, \\ u_{stw-sosm} &= k_1||s||^{1/2}sign(s) - z_2, \\ \dot{z_2} &= -k_2 sign(s) \end{aligned} \tag{4.30}$$

From (4.29) and (4.30), the closed loop error dynamics are given by

$$\begin{aligned} \dot{s} = -k_1||s||^{1/2}sign(s) + z_2 + \rho(t, x_1, x_2), \\ \dot{z_2} = -k_2 sign(s). \end{aligned} \tag{4.31}$$

The sliding gains are selected as follows to guarantee the stability and convergence of the system [231]:

$$\begin{aligned} k_1 &> 2\bar{\varepsilon}, \\ k_2 &> k_1 \frac{5k_1 + 4\bar{\varepsilon}}{(2k_1 - 4\bar{\varepsilon})}\bar{\varepsilon}, \end{aligned} \tag{4.32}$$

and then the sliding surface $s$ is stable and converges to zero in finite time.

Remark 1. Because $\bar{\varepsilon}$ is the bound value of the STW-TOSM estimation error, we can determine this value based on experiments by observing the STW-TOSM estimation error. However, due to the estimation capability of the sliding mode observer, the observer error is usually very small. Thus, the sliding gains can be selected as a small value to guarantee the condition (4.32).

Remark 2. [110], No matter what the control input is, the STW-TOSM observer can obtain a finite time convergence [112]. This means that the controller and observer (4.18) can be designed separately. Therefore, if the stability of the observer and controller can be guaranteed separately, the closed loop observer-controller can be successfully applied without any stability problem.

Table 4.2 – Comparison between different methods of FTC

| Methods | Stability | Convergence | Tolerant fault | Tracking control |
|---|---|---|---|---|
| SMC | Not sure | Converge | Constant fault | Yes |
| STW-SMC | Stable | Converge | Time-varying fault | Yes |
| Distrubance observer (DO) | Stable | Converge | Constant fault | Yes |
| DO + Neural Fuzzy | Not sure | Converge | Time-varying fault | Not sure |

## 4.5 Simulations and results

In order to verify the effectiveness of the proposed FD and FTC algorithm, its overall procedure is simulated for a robot manipulator in which the five joints are used. The simulations are divided into two sets to verify the capability of the proposed FD and FTC schemes, respectively. We will illustrate the capability of the STW-TOSM observer in state estimation and fault detection and isolation.

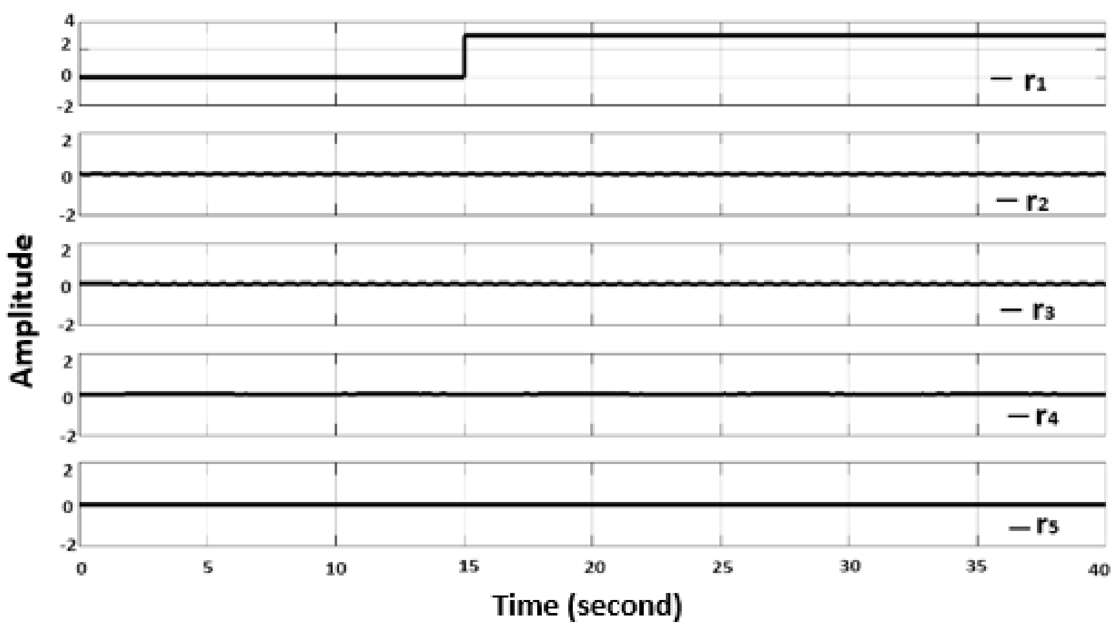



Figure 4.4 – Residuals evolution of the system with fault in the articulation 1.

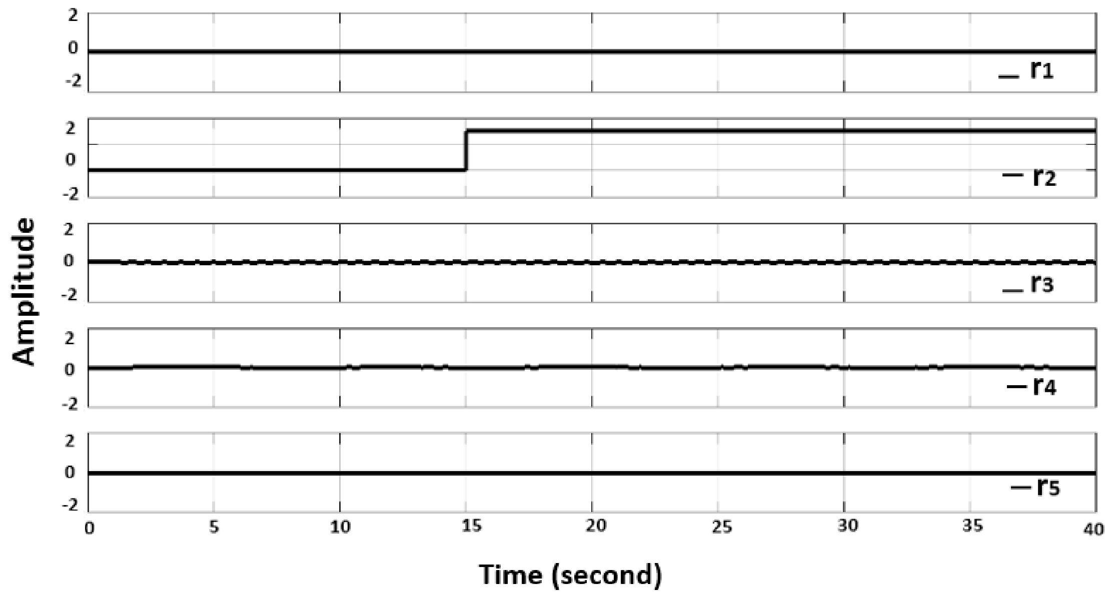



Figure 4.5 – Residuals evolution of the system with fault in the articulation 2.

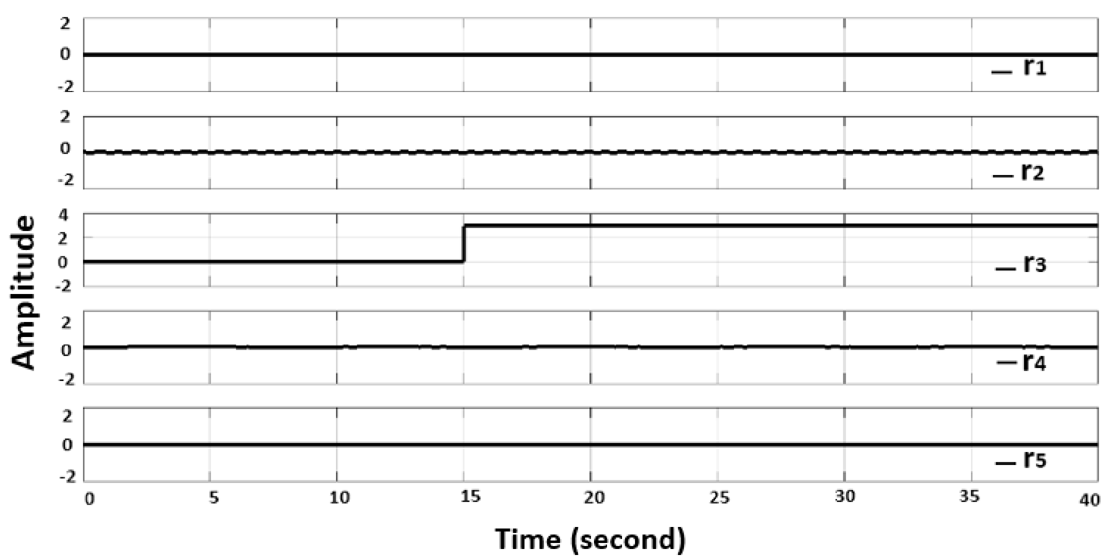



Figure 4.6 – Residuals evolution of the system with fault in the articulation 3.

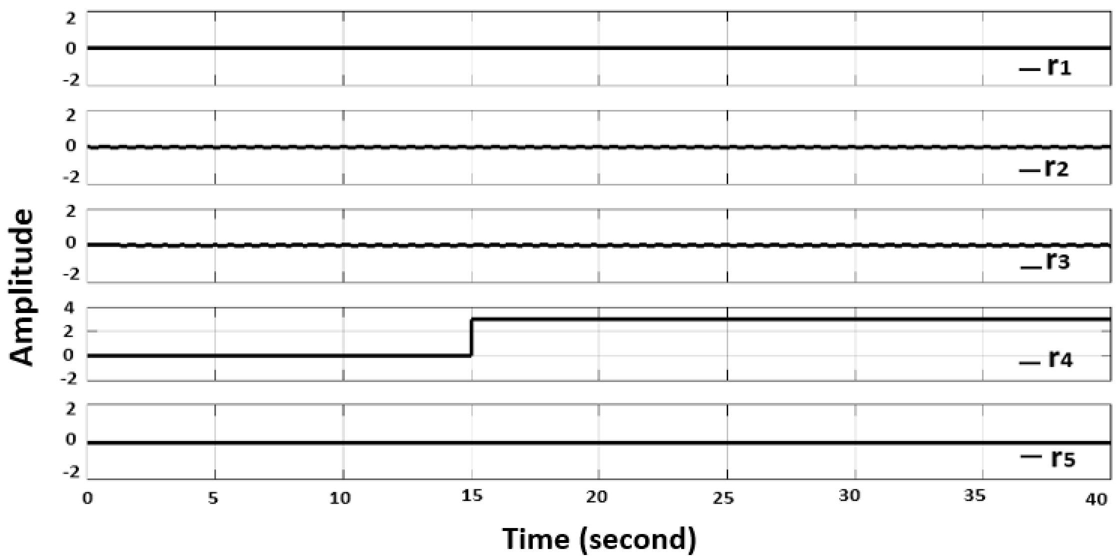



Figure 4.7 – Residuals evolution of the system with fault in the articulation 4.

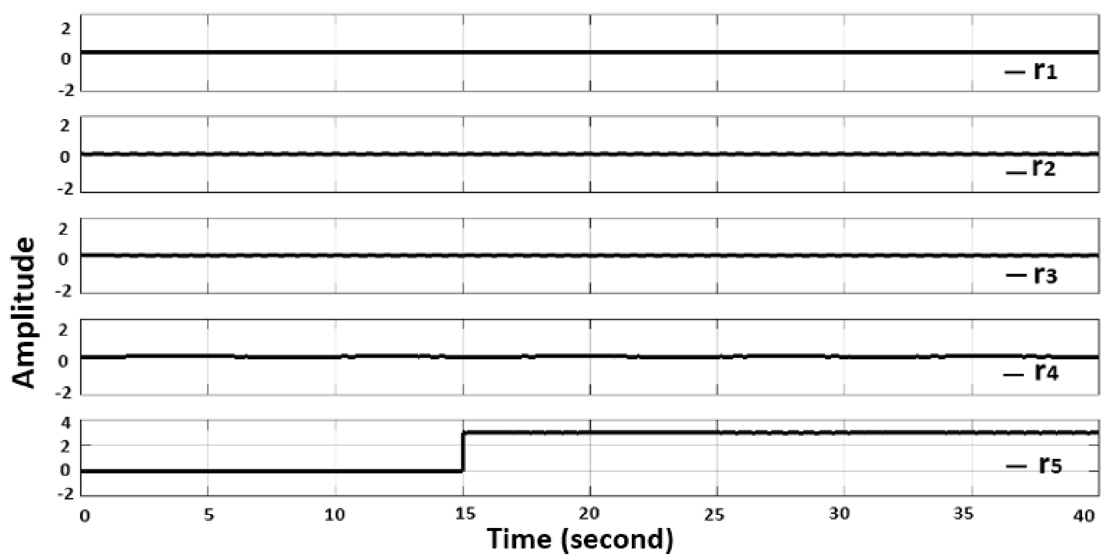



Figure 4.8 – Residuals evolution of the system with fault in the articulation 5.

After the injection of an abrupt fault in the system, the fault is appeared in the sensors at $T = 15s$ and the simulation of the system during the time of $T = 40s$. The residuals under the effect of the given fault are illustrated in figures (4.4, 4.5, 4.6, 4.7, 4.8), we can see that the different residuals react according to the fault signature table. The real and estimated states of the STW-TOSM observer in the case of sensor faults are shown in Figures (4.9, 4.10, 4.11, 4.12, 4.13).

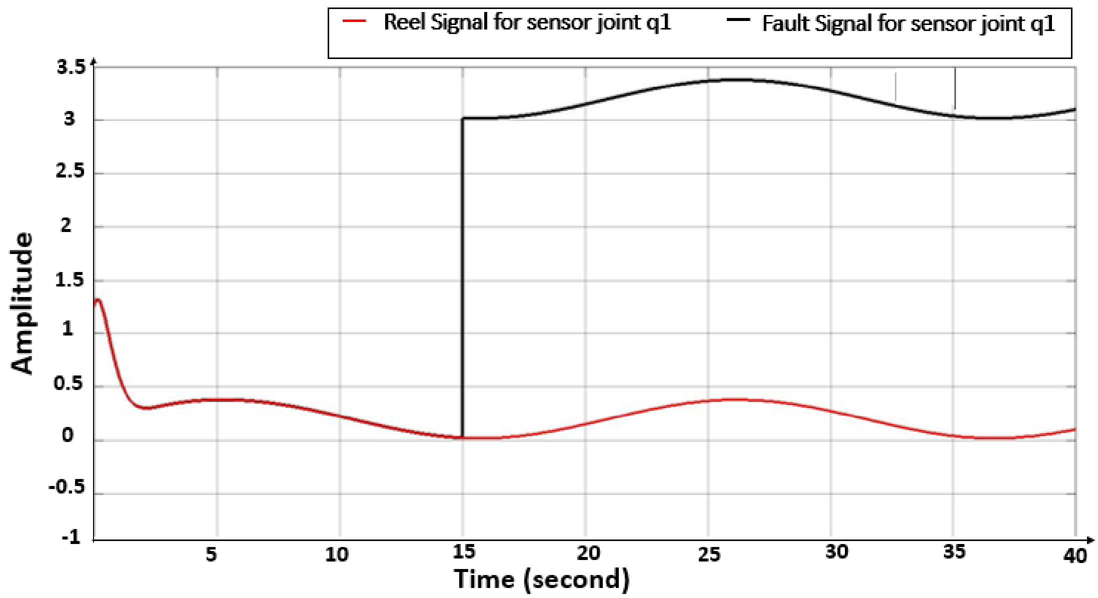



Figure 4.9 – Simulation of FDI on the first sensor. Detection and isolation of the faults by using STW-TOSMO.

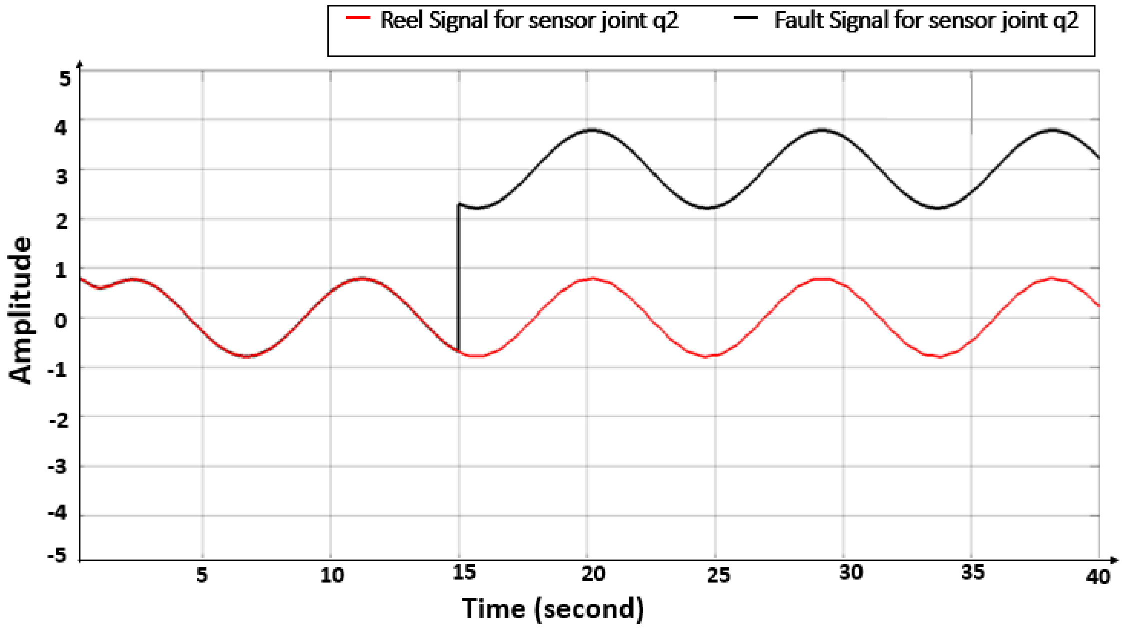



Figure 4.10 – Simulation of FDI on the second sensor. Detection and isolation of the faults by using STW-TOSMO.

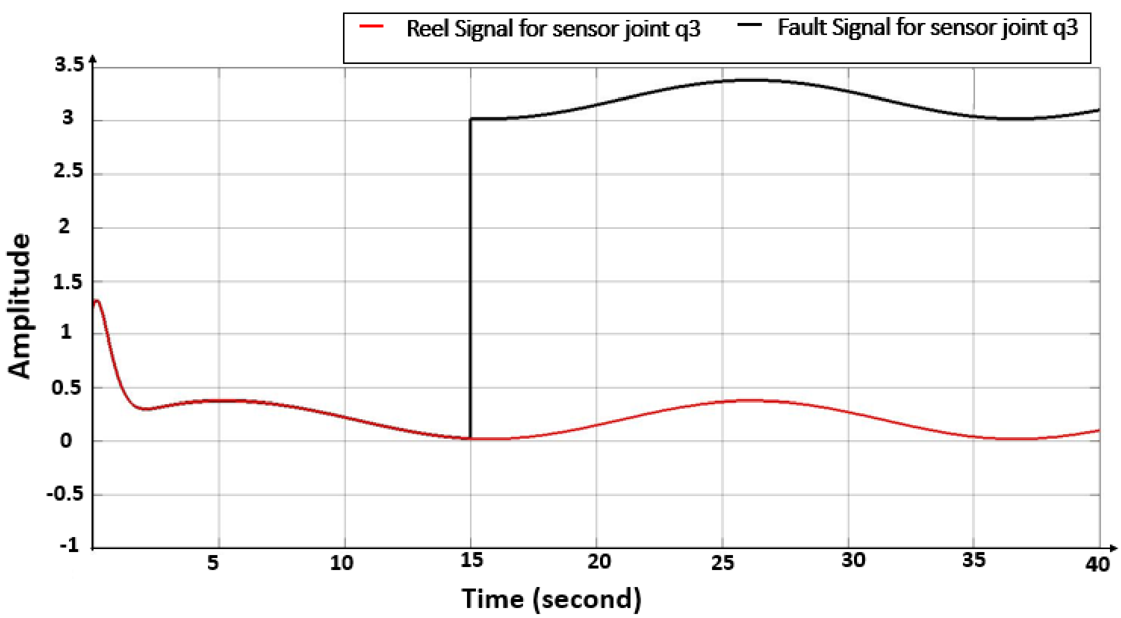



Figure 4.11 – Simulation of FDI on the third sensor. Detection and isolation of the faults by using STW-TOSMO.

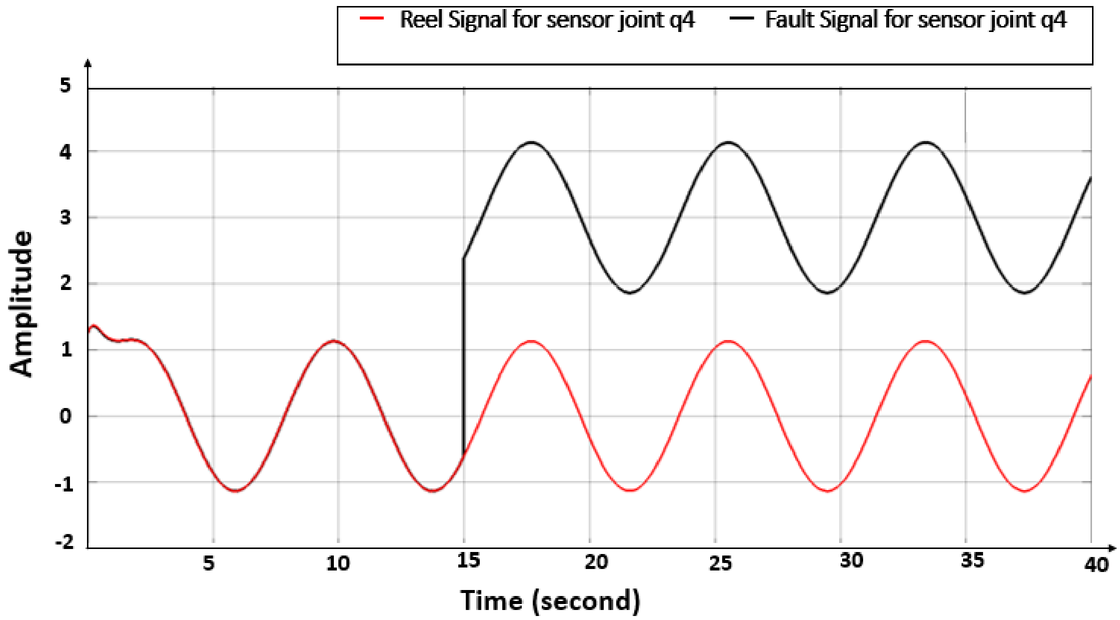



Figure 4.12 – Simulation of FDI on the fourth sensor. Detection and isolation of the faults by using STW-TOSMO.

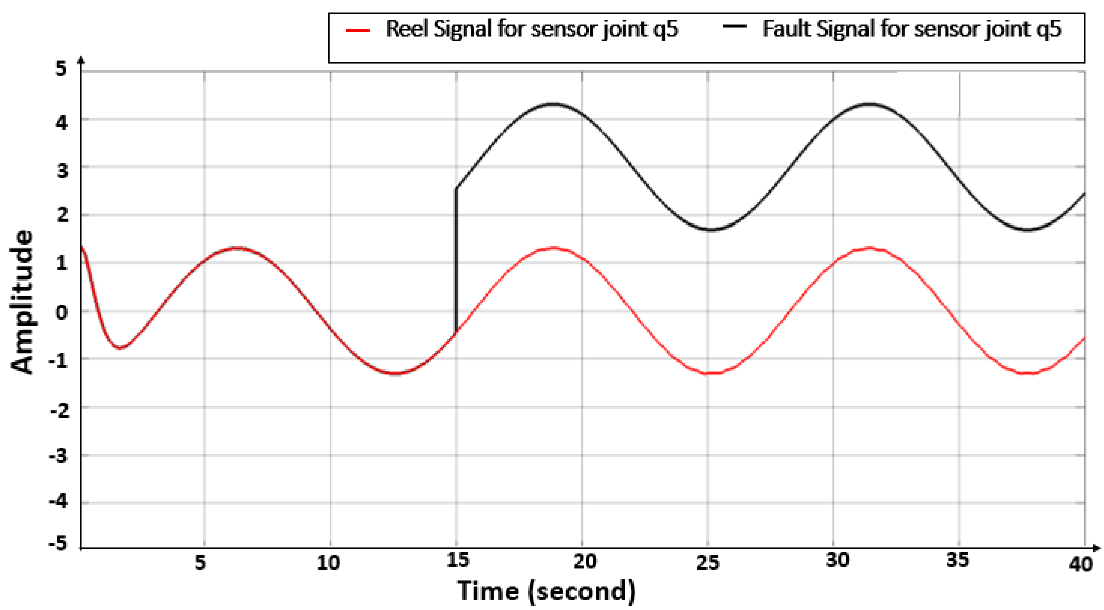



Figure 4.13 – Simulation of FDI on the five sensor. Detection and isolation of the faults by using STW-TOSMO.

Therefore we can conclud that the fault is correctly detected and isolated. So, the

STW-TOSM observer provides a good estimation without filtration. For this reason, it is used as the residual to detect and isolate the faults.

Finally, the proposed FDI methods can give a good results in comparison between the original state and the state estimated, therefore the state estimate converges to the actual state rapidly, that's why we find the residuals equal to zero. So this methods detect and isolate the sensor faults in a robot manipulator.

In the second part of the simulation, the performance of the proposed active FTC is shown. The goal of the control system is to follow the desired trajectory $x_d = [x_{1d}, x_{2d}, x_{3d}, x_{4d}, x_{5d}]$. Figures (4.14, 4.15, 4.16, 4.17, 4.18) show the desired trajectories and joint angles for each joint of the robot manipulator when a fault occurs under the active STW-SOSM-FTC.

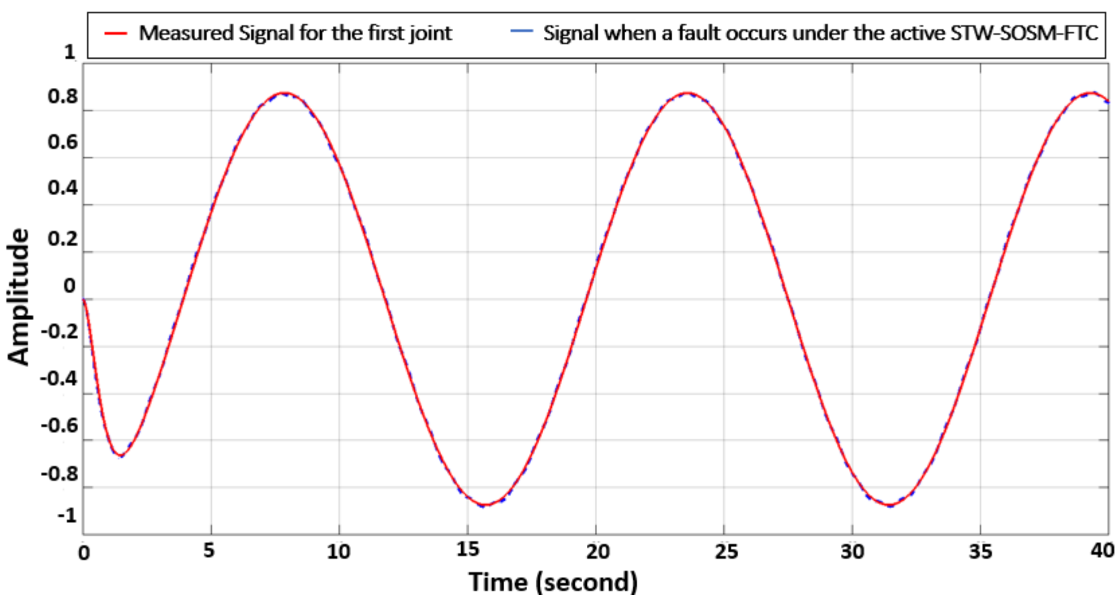



Figure 4.14 – The desired trajectories and joint angles number 1 of the robot manipulator when a fault occurs under the active STW-SOSM-FTC.

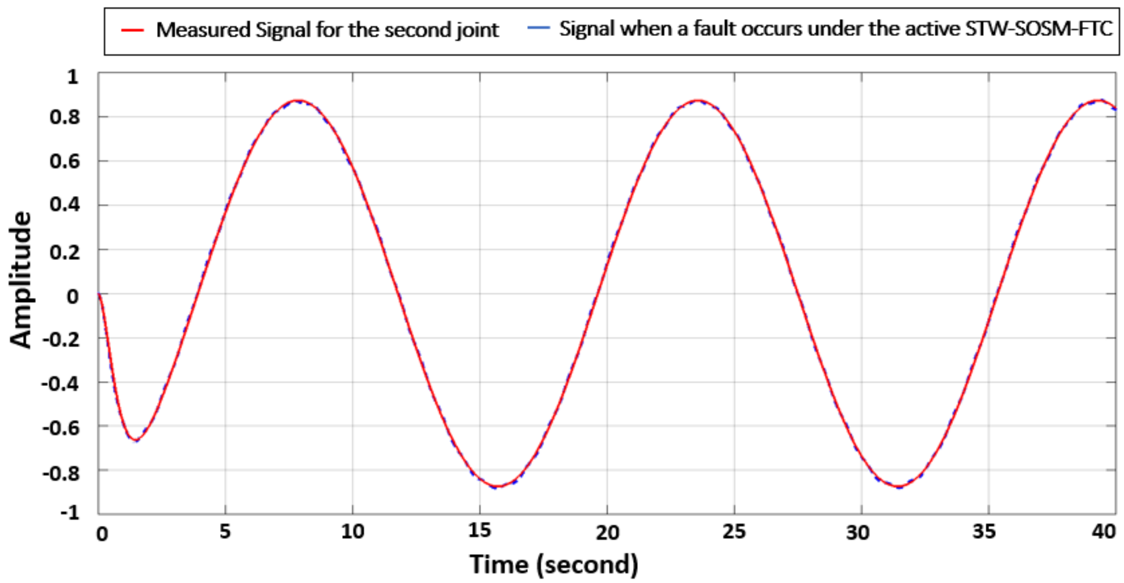



Figure 4.15 – The desired trajectories and joint angles number 2 of the robot manipulator when a fault occurs under the active STW-SOSM-FTC.

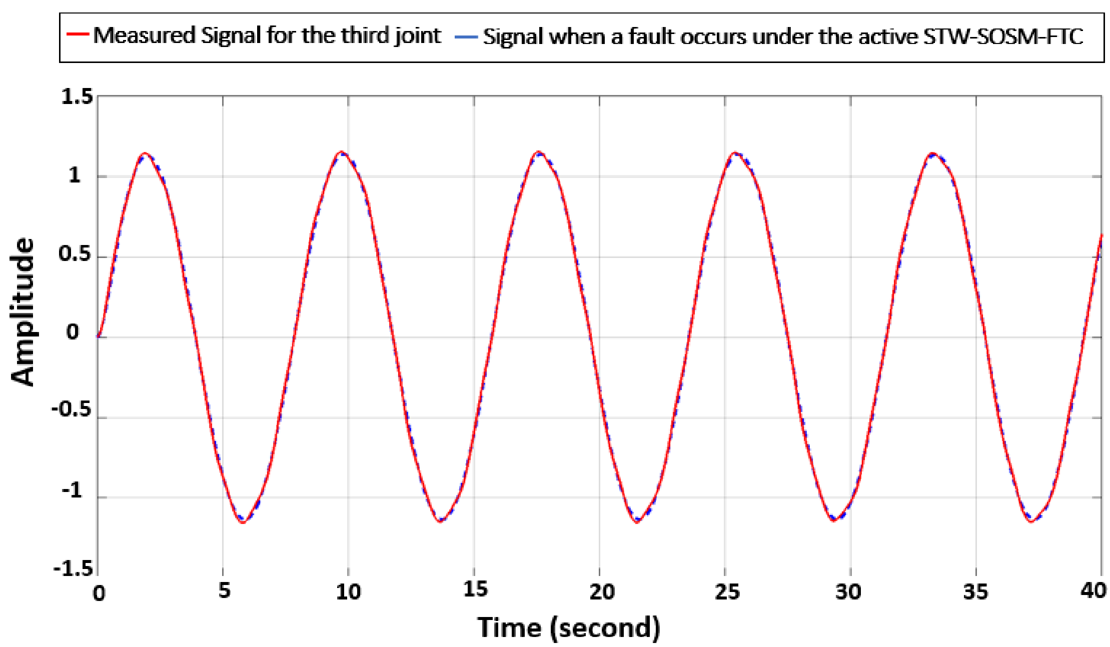



Figure 4.16 – The desired trajectories and joint angles number 3 of the robot manipulator when a fault occurs under the active STW-SOSM-FTC.

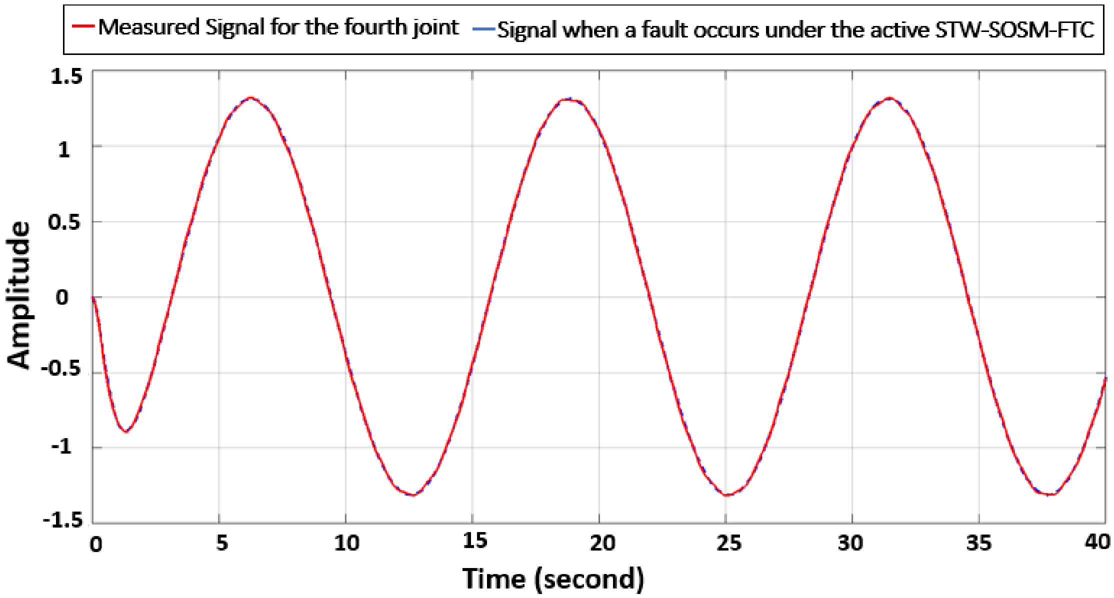



Figure 4.17 – The desired trajectories and joint angles number 4 of the robot manipulator when a fault occurs under the active STW-SOSM-FTC.

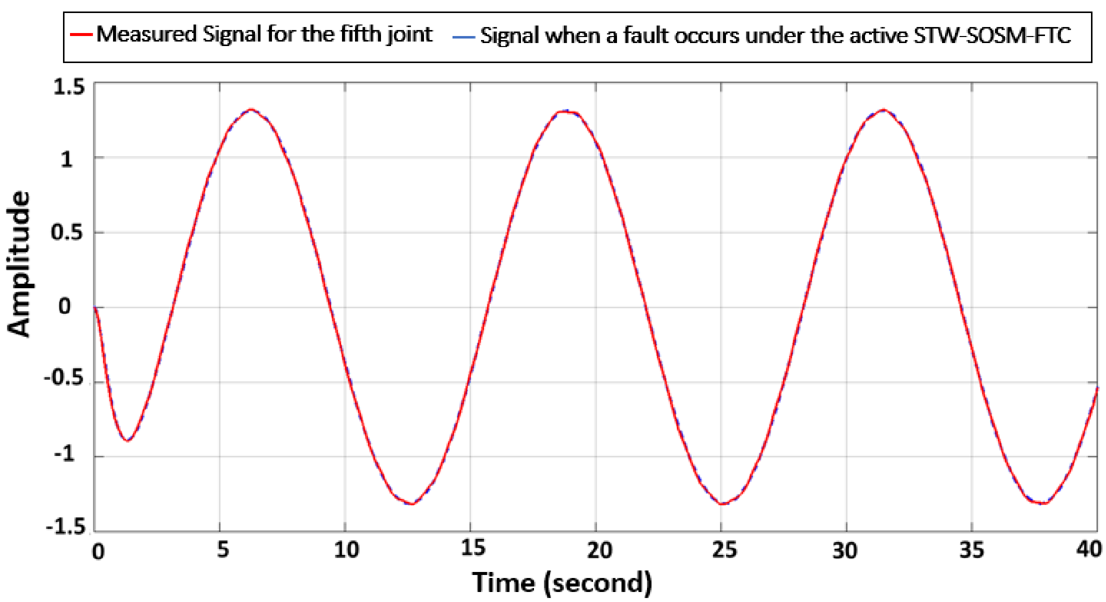



Figure 4.18 – The desired trajectories and joint angles number 5 of the robot manipulator when a fault occurs under the active STW-SOSM-FTC.

In order to exhibit the superior performance of the proposed active FTC based on STW-SOSM (active STW-SOSM-FTC), we compared it with the traditional SM. The performance of the active STW-SOSM-FTC is better than the classical SM-FTC. As we can see in the figures (4.19, 4.20, 4.21, 4.22, 4.23), the chattering with active STW-SOSM-FTC is more reduced than classical SM. Therefore the active STW-SOSM-FTC has great fault tolerance capability and great robustness to external disturbances and system uncertainty.

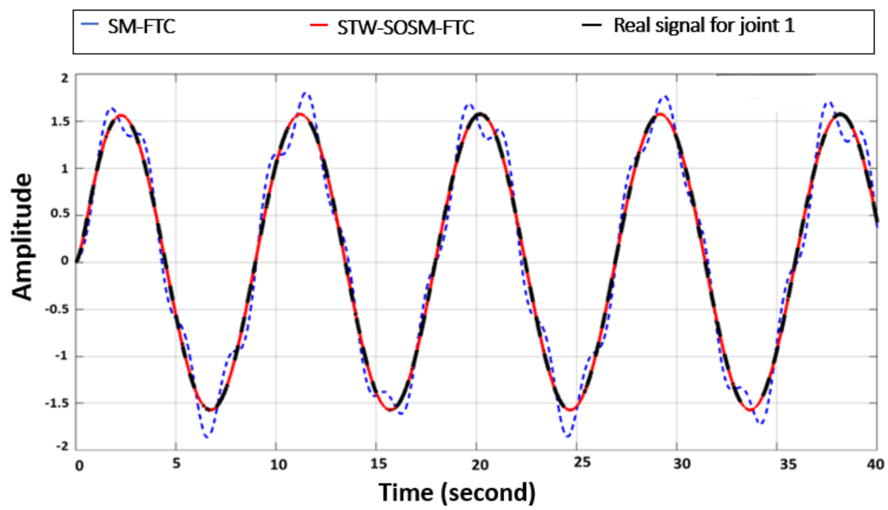



Figure 4.19 – Comparison between the active FTC by SMC and STW-SOSM for articulation 1.

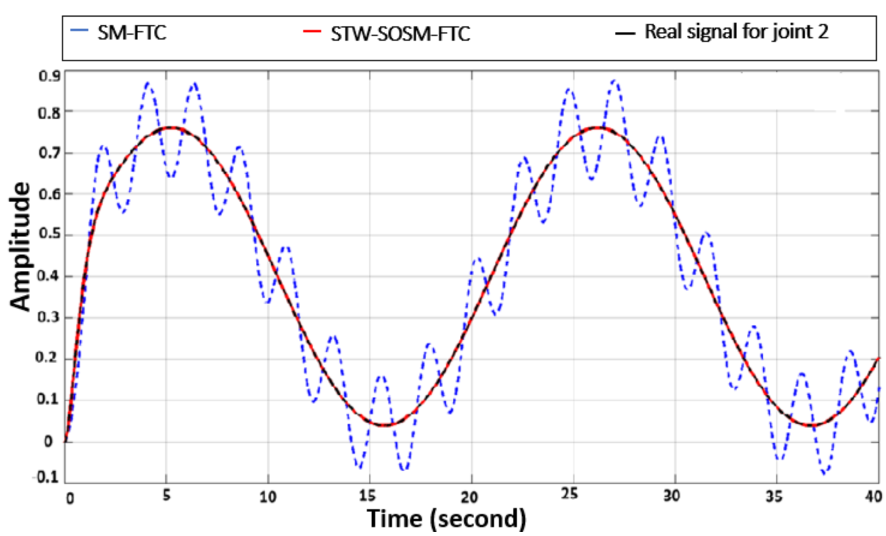



Figure 4.20 – Comparison between the active FTC by SMC and STW-SOSM for articulation 2.

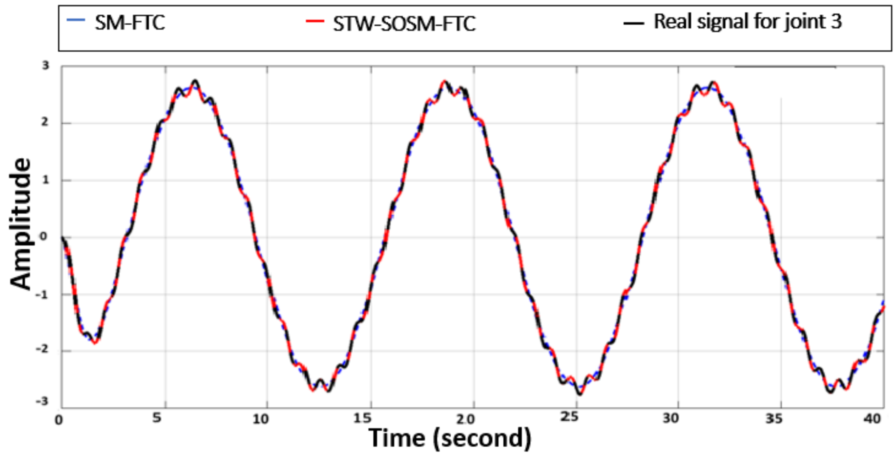



Figure 4.21 – Comparison between the active FTC by SMC and STW-SOSM for articulation 3.

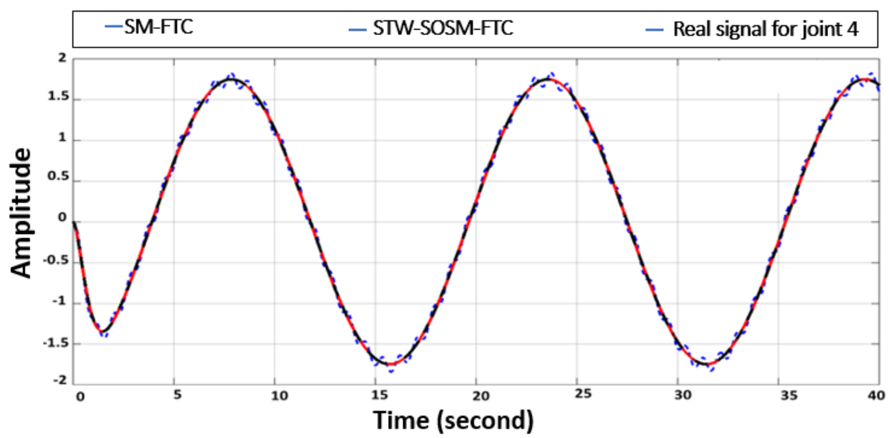



Figure 4.22 – Comparison between the active FTC by SMC and STW-SOSM for articulation 4.

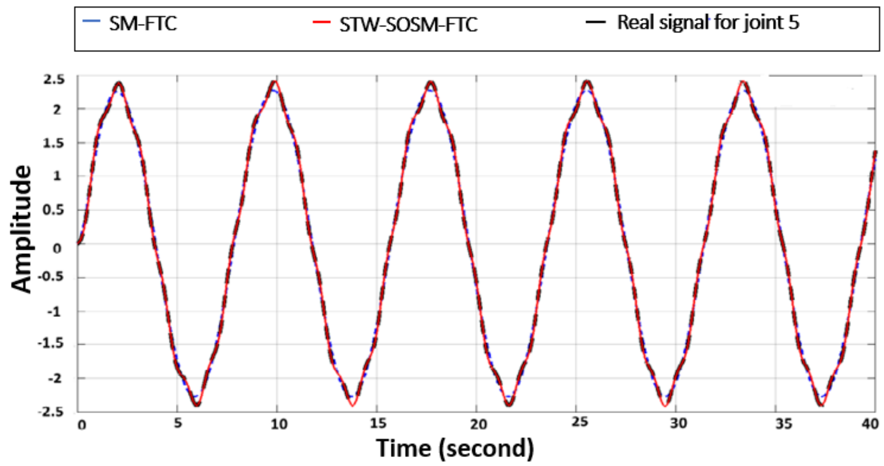



Figure 4.23 – Comparison between the active FTC by SMC and STW-SOSM for articulation 5.

The active FTC schemes based on STW-SOSM has acceptable performance and stability for a healthy system as well as for a faulty system. Therefore, active STW-SOSM-FTC gives higher accuracy, fast convergence and eliminates chattering.
In recent development of control engineering, advanced control schemes are well established for the systems under the influence of parametric uncertainties due to modelling error, nonlinearities, and the external disturbances. Among the different robust control schemes sliding mode control (SMC) has made attention for the control engineer due to its merits. SMC has grown rapidly as a control in comparison with other robust control strategies due to its distinguish features like insensitive to matched uncertainties, reduced order sliding mode equations, zero error convergence of closed loop system and it offers a nonlinear control.
Compared with the typical existing fault tolerant control methods, SMC, disturbance observer method, the STW-SMC and the disturbance observer plus neural-fuzzy network method, the advantages of the proposed method are listed in Table (4.2).
The STW-SMC is more robust than the SMC and the disturbance observer plus neural-fuzzy network. Figure (4.19, 4.20, 4.21, 4.22, 4.23) show, though, SMC has chattering in the presence of uncertainty, nevertheless, it is more robust than most of the traditional nonlinear model reference controllers e.g., feedback linearization method. Therefore,

STW-SOSM show the robustness comparing with SMC.

## 4.6 Conclusion

In this chapter, the two-fold approach was successfully proposed. In the first part, a fault diagnosis scheme based on the STW-TOSM observer was designed. The equivalent output injection of the STW-TOSM observer, which accurately obtains the unknown input without filtration, was used as a residual for fault detection and isolation. A fault is detected and isolated whenever the residual exceeds its corresponding threshold. In the second part, an active FTC scheme based on a combination of the STW-TOSM observer and the STW-SOSM controller was designed. The proposed FTC scheme could accommodate the fault and the uncertainties, and it did not require a velocity measurement. The analysis and simulation results for a robot verify that the proposed Active STW-SOSM-FTC has excellent fault tolerance capability and great robustness to external disturbances and system uncertainty. From these results, one can notice that the proposed method for fault-tolerant control has better performances in terms of fast response speed, smaller tracking error and better compensation performance to sensor faults.

# CONCLUSION AND FUTURE WORK

In the industry and industrial production, the field of competitiveness is based on several criteria of performance, robustness and quality. But despite all the diligence in establishing these designs, their failures are frequent and can result either from the end of an element's life cycle and also from the sudden appearance of a sudden failure. While these production elements mostly represent major issues either for profit or to provide a service. They can also touch on a most important element which represents material, environmental, and even human security. To avoid irreversible consequences, fault detection and isolation methods have been put in place and which are all based on system diagnosis. In certain complex systems, the phase of detecting and locating one or more faults is necessary but is not sufficient to guarantee operating safety because it is essential to modify the control law in real time in order to maintain the system stability and thus guarantee acceptable operation in degraded mode. Thus, it is necessary to associate a fault-tolerant control law with the diagnosis.

Fault tolerant systems are divided into two main families with on the one hand a passive approach and on the other hand the active channel approach including a diagnosis module. A large number of publications present the field of fault tolerant control, but most deal with linear systems or systems operating in a restricted field. In this context, our objective was to develop control laws tolerant to faults in non linear systems. As a result, two major axes have been developed: One in the area of fault detection and isolation and the other in the area of fault tolerant control on such systems. The effectiveness and the robustness of the developed approaches have been demonstrated using a 5-DOF modular and reconfigurable robot.

The fault detection and isolation survey in the second chapter has devoted to the methods most used in the literature by analyzing the advantages and limitations of these tools and by motivating the use of model-based methods. The objective of several recent works is to develop fault detection and isolation techniques that are robust to uncertainties, and measurement errors. In our thesis, we focused on observer based fault detection and isolation approach. The first part of this work exposed sensor fault based on high gain observer technique. This observer is used to estimate the state system for a non-linear system with the assumption that the system is observable. The design process for high-gain observer is very simple; the observer gain is determined based on a positive constant that should be selected as small as possible to have a fast state estimation. The choice of the parameters gain is the major drawback of this method. This problem of high-gain observer is the so-called peaking phenomenon (the state estimation exhibits a large output during transients), but such an issue can easily be solved by saturating the control input during transients. Note that the control saturation does not affect the transient performance of the closed-loop system, as the state observer can compensate for the effect of the saturation blocks. For this reason we have chosen the gain with two different strategy. In the second part of the thesis, we have proposed another approach based on higher order sliding mode observer and have been addressed for actuator fault. This method is stable and robust against system uncertainties and external disturbances. Therefore, higher order sliding mode observer remove the chattering phenomenon that appear with the traditional sliding mode observer. The results demonstrate the effectiveness of the fault detection and isolation method about the performance of certain qualities such as the speed of detection and isolation, minimization of false alarms and bad detections.

The last part this work described the fault-tolerant control technique for robot manipulators. Firstly, a fault diagnosis scheme based on the Super Twisting Third Order Sliding Mode (STW-TOSM) observer was designed. A fault is detected and isolated whenever the residual exceeds its corresponding threshold. In the second part, an active FTC scheme based on a combination of the STW-TOSM observer and the Super Twisting Second Order Sliding Mode (STW-SOSM) controller was designed. The analysis and simulation results for the robot manipulator verify that the proposed Active STW-SOSM fault tolerant control has excellent fault tolerance capability and great robustness to external disturbances and system uncertainty. From the obtained results, we can notice that the proposed method for fault-tolerant control has better performances in terms of fast response speed, smaller tracking error and better compensation performance to sensor faults. For both, the result of FDI and FTC conducted in this thesis allowed us to develop an FDI and FTC algorithms for robot manipulators that give excellent results.

As perspective, these techniques will be practically tested in a real robot in order to validate the proposed approaches. We have proposed in this thesis model-based fault detection and isolation methods and specifically quantitative methods. In the future work, we would like to extend the scope of this work to include other techniques based on qualitative methods such as Neural Network and Genetic Algorithms that can provide an excellent avenue to improve the overall system performance.

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## ROBOT'S PARAMERTERS

1- Structure of $M(q,\dot{q})$ and $F(q,\dot{q})$:

$M(1,1) = I_{zz1} + I_{zz2} + I_{zz3} + 2m_3L^2c_{23} + 2m_2L^2c_2 + 2m_3L^2c_3 + 2m_3L^2c_2 + m_1L^2 + 2m_2L^2 + 3m_3L^2$

$M(2,1) = I_{zz2} + I_{zz3} + 2m_3L^2c_3 + m_3L^2c_2 + m_2L^2c_2 + m_3L^2c_{23} + 2m_3L^2 + m_2L^2$

$M(3,1) = I_{zz3} + m_3L^2 + m_3L^2c_3 + m_3L^2c_{23}$

$M(1,2) = M(2,1)$

$M(2,2) = I_{zz2} + I_{zz3} + 2m_3L^2 + m_2L^2 + 2m_3L^2c_3$

$M(3,2) = I_{zz3} + m_3L^2 + m_3L^2c_3$

$M(1,3) = M(3,1)$

$M(3,3) = I_{zz3} + m_3L^2$

$F(1) = -L^2(m_3\dot{q}_2{}^2s_2 + m_3\dot{q}_2{}^2s_3 + m_3\dot{q}_2{}^2s_23 + m_3\dot{q}_3{}^2s_23 + 2m_3\dot{q}_3\dot{q}_1s_23 + 2m_2\dot{q}_1\dot{q}_2s_2 + 2m_3\dot{q}_1\dot{q}_2s_2 + 2m_3\dot{q}_2\dot{q}_3s_3 + 2m_3\dot{q}_1\dot{q}_3s_3 + 2m_3\dot{q}_1\dot{q}_2s_23 + 2m_3\dot{q}_2\dot{q}_3s_23$

$F(2) = L^2(-2m_3\dot{q}_1\dot{q}_3s_3 - m_3\dot{q}_3{}^2s_3 - 2m_3\dot{q}_3\dot{q}_2s_3 + m_3\dot{q}_1{}^2s_23 + m_3\dot{q}_1{}^2s_2 - m_2\dot{q}_1{}^2s_2)$

$F(3) = m_3L^2(2\dot{q}_1\dot{q}_2s_3 + \dot{q}_1{}^2s_23 + \dot{q}_2{}^2s_3 + \dot{q}_1{}^2s_3)$

where $c_i = cos(q_i)$, $c_{ij} = cos(q_i + q_j)$, $si$ = $sin(q_i)$, and $s_{ij} = sin(q_i + q_j)$.

2- Kinematic parameters:

$L = 0.1228m$.

3- Estimated dynamics parameters:

$m1 = m2 = m3 = 3kg$

$I_zz1 = I_zz2 = I_zz3 = 0.0038kgm^2$.

US006323615B1

(12) **United States Patent**
**Khairallah**

(10) **Patent No.: US 6,323,615 B1**
(45) **Date of Patent: Nov. 27, 2001**

(54) **MODULAR ARTICULATED ROBOT STRUCTURE**

(76) Inventor: **Charles Khairallah**, Apartment 1203, 1650 Lincoln, Montreal, Quebec (CA), H3H 1H1



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(57) **ABSTRACT**

A modular articulated robot structure (FIG. **4**) composed of a series of independent modules (**10,100,300**) releasably connected to each other to form various configurations. The modules (**10,100,300**) may be of the rotary (**10**), linear (**100**), or wheeled (**300**) type. The rotary modules (**10**) are generally formed of first and second substantially U-shaped structural members (**12,14**) pivotally attached to one another by means of a pair of axles or pivot pins (**26**) adapted to support a workload exerted on the module (**10**). A motor (**48**) is mounted internally of the module (**10**) for pivoting the second structural member (**14**) relative to the first structural member (**12**). The motor (**48**) is connected to the second structural member (**14**) in such a way that it is not submitted to outside loads exerted on the module (**10**). Typically, the first and second structural members (**12,14**) are provided with cooperating abutment surfaces (**17,19,74,76,78,80**) for increasing the overall structural rigidity of the module (**10**) in certain positions thereof.

**25 Claims, 11 Drawing Sheets**