SLIDING MODE OBSERVER DESIGN FOR SENSOR FAULT DIAGNOSTIC OF A MECHATRONICS SYSTEM

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by

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LIST OF ABBREVIATIONS

emf	Electromotive force
DC	Direct Current
IAE	Integral Analysis Error
Hz	Hertz
CPS	Cyber-physical system
MRAS	Model Reference Adaptive System
T-S	Takagi-Sugeno
FTA	Fault tree analysis
FEM	Finite element method
AI	Artificial intelligence

LIST OF SYMBOLS

T	Torque
K_t	Motor torque constant
i	Armature current
e	Back emf
K_e	Electromotive force constant
$\dot{\theta}$	Angular speed
J	Moment of inertia of rotor
$\ddot{\theta}$	Angular acceleration
b	Motor viscous friction constant
K	Motor torque constant and electromotive force constant
L	Electric inductance
R	Armature resistance
v	Voltage
Θ	Angular position
Ω	Ohm
s	Laplace variable
sgn(.)	Signum function
$\Re$	Real numbers
$\Re^{n\times m}$	Set of real matrices with n rows and m columns

REKA BENTUK PEMERHATI ‘SLIDING-MODE’ UNTUK DIAGNOSTIK SENSOR YANG RALAT DALAM SISTEM MEKATRONIK

ABSTRAK

Pengesanan ralat memainkan peranan yang penting dalam bidang pembuatan kerana dapat membantu pengusaha untuk mengesan sistem yang ralat lebih awal sebelum memberikan kesan pada keseluruhan proses. Pengesanan dan pampasan adalah lebih penting dalam sistem yang saling berkaitan, contohnya manipulator pelbagai robot digunakan untuk melaksanakan tugas kerjasama. Keterhubungan dalam sistem yang bermaksud setiap subsistem bergantung antara satu sama lain untuk melakukan tugasan yang diberikan, sistem anggaran harus digunakan yang dapat membantu untuk menganggarkan kesihatan keadaan subsistem. Dalam projek ini, pemerhati lurus dipelajari pada mulanya dan disimulasikan di bawah keadaan maklum balas pengekod yang tidak bagus. Kajian ini diperluaskan kepada perumusan bukan lurus yang teguh menggunakan teori ‘Sliding Mode’. Model keadaan ruang mewakili dinamik motor DC yang dikaji menukar terlebih dahulu menjadi bentuk kanonik nominal sebelum pemerhati tidak lurus yang teguh direka. Jenis ralat yang diperkenalkan terhadap maklum balas sensor pengekod adalah dalam bentuk Gaussian putih yang tidak bagus (dibatasi). Simulasi pemerhati bukan lurus yang teguh dalam membina semula maklum balas sensor yang ralat membaca semula terhadap kejayaan penumpuan kepada nilai kedudukan yang sebenar. Ini diteruskan dengan sokongan daripada eksperimen dengan menggunakan motor DC yang sebenar yang dilengkapi dengan pengekod. Ralat diperkenalkan melalui konsep perkakasan dalam gelung menggunakan set blok Simulink.

SLIDING-MODE OBSERVER DESIGN FOR SENSOR FAULT DIAGNOSTIC OF A MECHATRONICS SYSTEM

ABSTRACT

Fault detection plays an important role in the manufacturing area as it can help the manufacturer to detect the faulty system earlier before it can affect the overall processes. Fault detection and compensation are even more crucial in an interconnected system, giving an examples of multi-robot manipulators are employed to perform cooperative task. Interconnectedness within the system which means each subsystem is depend on each other in order to do the task given, an estimation system must be deployed which can help to estimate the health of subsystem condition. In this project, a linear observer is studied at first and simulated under a noisy encoder feedback scenario. The study is further extended to the formulation of robust nonlinear observer utilizing the theory of sliding mode. The state-space model representing the dynamic of the studied DC motor is transformed first into a nominal canonical form before the robust nonlinear observer is designed. The fault type introduced in an encoder sensor feedback is in a form of white Gaussian noise (bounded). Simulation of the robust nonlinear observer in reconstructing the corrupted sensor feedback rereads the successful convergence to the true position value. This is further supported by experimentation using the real DC motor which is equipped with an encoder. The fault is introduced via hardware-in-the-loop concept using Simulink block set.

CHAPTER 1

INTRODUCTION

1.1 Overview

Nowadays, the Industry 4.0 is widely regarded as the latest industry that took a place into most of industry as well as play an important role to keep track with the current technology to create an efficient system and produce a product which fulfill the customer needs. The word Industry 4.0 refer to the fourth industrial revolution. In the context of Industry 4.0, an intelligent manufacturing took place as it has the ability to create a cyber twin of the physical system, monitor physical processes, and the decisions are decided through real-time communication and cooperation with humans, machines and others (Zhong et al., 2017).

Thus, the Industry 4.0 can be further explored through the Smart Product, the Smart Machine and the Augmented Operator (Mrugalska and Wyrwicka, 2017). By implementing Industry 4.0 in manufacturing process, many advantages over disadvantages had accomplished. Although it is popular among industry, the Industry 4.0 is still a comparatively new method of managing production process and there might be an error or new types of risks will occur due to some more complex part that already installed into their system (Tupa et al., 2017). In order to achieve better process efficiency, every aspect that can be influenced need to be considered and looked carefully. Moreover, a highly flexible production model and digital products or services had been constructed within Industry 4.0 as it interact between people, products and machines during the manufacturing and production process (Zhou et al., 2015).

In the context of Industry 4.0, an operation system is controlled via cyber-physical system (CPS) in a network where human supervision is least required. Thus, the total cost and amount can be reduced as it will be supported and controlled by computer-based interconnection of machines and components that will automatically operate the system based on the predetermined instructions (Marcon et al., 2017). Directly or indirectly, the productivity of manufacturing industry will increase and will be a further boost to the working environment around the workers.

In order to make sure the production lines run continuously and working without any error, we need to make sure the condition or healthy of the subsystem are in a good condition. This is to prevent any further problem that will affect the whole system because it is consist of a network of several system or called interconnectedness between each subsystem. If one of the subsystem breakdown, another subsystem must be disrupted or delayed or even at critical condition, it need to be stopped. The alternative way to prevent from this happen, we need a mechanism that can detect the problem faced during the production lines and thereby, the problem can be resolved during the time of low production.

Therefore, we need an estimation system that can estimate the health of the subsystem. By employing a state-of-the-art control strategy. A state observer can be introduced and implemented to reconstruct the states of the system. At the same time, the condition of any subsystem can be known whether they are healthy or vice versa by performing state observation. An observers are algorithms that combine sensed signals with other knowledge of control system to produce observed signal which can be used to replace sensors in a control system (Ellis, 2002a). It is also defined as a dynamic system that is used to estimate the state of a system or some of the states of a system. Its purpose is to generate an estimate of the state based on measurement of a system output and system input which input and output of signal are assumed to be exactly measurable. Hence, a state estimator or an observer can be designed to identify and detect the fault in a system by providing an estimated output which is then compared with the measured output and evaluated with a decision making algorithm (Mohamadi et al., 2016). This can be explained by looking to Figure 1.1.

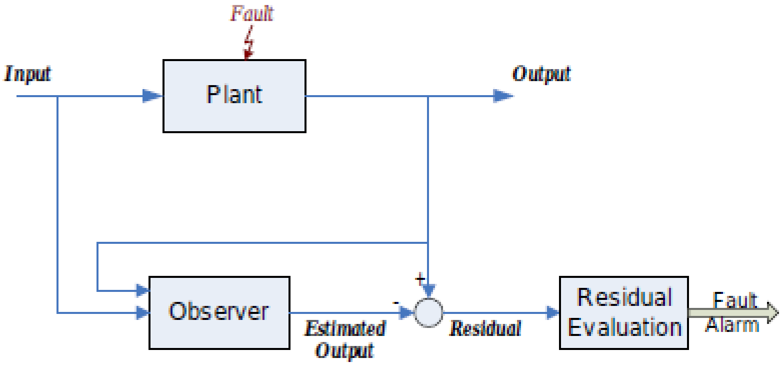

Figure 1.1 – Model based fault detection (Mohamadi et al., 2016)

1.2 Motivation

To illustrate the concept of an observer in this project, DC motor is to be used as a platform. DC motor is regarded as a commonly actuator widely used in control applications for most industry today. As many industrial involving automation growing rapidly, the use of a machine that involving mechanical and electrical part must be widely used especially the use of DC motor which it is been use in the machine or a system to rotate or move something from one position to another position. High performance is usually demanded of dc drives. Thus, DC motor is a suitable to be investigated that act as actuator.

The actuator is actually a moving component or power device that produces the input to the plant according to the control signal that will affect the output signal to approach the reference input signal (Ogata, 2009). Together, the encoder will include in the system that act as a sensor because all industries used the encoders in machinery for motion feedback and motion control. Sometimes, if the motor running at higher speed or at a longer time, the performance of the motor maybe can be reduced or any worst case the motor can be damage. Then, a new control techniques and design approaches need to be discovered to overcome that problem so that the failing subsystem can be detect early while the overall system stability and performance can be maintain (Khosravani et al., 2011).

Generally, control systems are susceptible to various failure caused by actuators, sensors and unpredictable parameter that are changing in the system (Lina and Hong, 2005). For this reason, research into fault diagnosis and fault-tolerant control are being implemented for many years (Ren et al., 2015). Thus, a sliding mode observer is an alternative way to diagnosis or estimate the problem and the failure of system.

1.3 Problem Statement

In the era of Industry 4.0, fault detection in a networking system in a factory will be a challenging problem (Roth et al., 2012). Fault needs to be accurately detected through estimation so that corrective actions can be taken precisely (Zhu et al., 2016). Next, an estimation should be accomplished in a fast manner to avoid prolonged in a down-time which may affect the productivity and the whole process (Menon and Edwards, 2014, Gao et al., 2015). The conventional estimation algorithm may be lacking in terms of estimation speed and its robustness.

1.4 Objectives

- To design a sliding mode observer to detect sensor fault in a DC motor with an encoder.
- To analyze the output feedback from a DC motor with an encoder.
- To develop numerical simulation and hardware demonstration kit to illustrate the fault-detection feature at sensor part.

1.5 Research Scope

This research work will concern on designing a sliding mode observer which estimates fault on sensor part which consisting of DC motor with an encoder that act as a sensor. Then, it will consist of two main part which are from software and hardware. On software via MATLAB, an observer is design using Simulink by applying state-space equation into the system and get the result based on simulation. While, for hardware part, we implement the real application using DC motor with an encoder and make a connection with the software part to test the fault detection functionality.

1.6 Thesis Structure

This thesis consists a total of 5 chapters. Chapter 1 is the introduction of the project. It contains the overview, motivation, problem statement, objectives and research scope.

For Chapter 2, the previous result done by other researchers are presents. The fault detection in dynamical system is reviewed as it plays a main task for this project. The concept of an observer as a system fault detection is studied in this project through the uses of different types of observer which focusses on three major observer which are linear observer, an adaptive observer and sliding mode observer. Besides that, other fault detection method is studied and investigated. Then, the observer versus other fault detection method is also reviewed.

In Chapter 3, the methodology used to accomplish this project is explained. The design for linear observer is explained through the state-space model. The sliding mode observer design is also explained in detail. The system equation and transfer function for DC motor is described in dynamic modelling. The implementation of hardware platform and software platform will be explained via this chapter.

Chapter 4 which focusses on the several test that have be done using the design or method of linear observer and sliding mode observer by using the simulation via MATLAB software. This chapter begin with the test of using the method of linear observer which implement the noise signal or without noise signal present in the system. This chapter is continued with the test of sliding mode observer method which implement in the noise present within the system. Then, by using a method of sliding mode observer, the model consisting of DC motor with an encoder is tested and demonstrate in real time to illustrate the sensor fault detection feature. All the testing results are discussed. Most of the results are displayed in the graph.

Chapter 5 is conclusion of this project. This chapter consist of overall deduction of this project, future recommendations and proposition to improve this project. The achievement of this project is also discussed and stated.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter will review work on fault detection as well as designing an observer to estimate the faulty system. This will further covering the fault detection in dynamical system which will be explain in section 2.2. While in section 2.3, the topic on an observer as system fault detector is discovered and reviewed. Together with linear observer (Luenberger observer), adaptive observer and robust observer (sliding mode observer) are discuss in subsection 2.3.1, 2.3.2 and 2.3.3 respectively. In addition, other fault detection method also be discovered in section 2.4. The most exciting and important section will be reviewed and discussed in section 2.5 which the content is covered about an observer versus other fault detection method. Finally, a quick recap for this chapter will be present in section 2.6.

2.2 Fault detection in dynamical system

The term of dynamical system refers to the big area including mechatronic, manufacturing, automotive system and others. As its application has taken place in industry, the information exchange has occurred and connected via a network in order to get the things become easily handled and save the times (Menon and Edwards, 2014). Due to the advanced technology and its design become more complex and hard to understand, the fault in the system may occur during the production line which is needed to overcome as it will affect the whole process and system.

A fault is simply defined as malfunction, unusual deviation of at least one criteria of its parameter or property which interrupt the control action and leading to system performance degradation (Gao et al., 2015). Sometimes, the word fault and failure looked the same but the meaning is different. We can differentiate this as the system failure are caused by the fault of the subsystem or machine due to its different reading from normal condition (Eissa et al., 2015). To improve the whole system working operation, the fault detection process is needed to avoid something bad happen and can be prevent from any worst cases.

Consequently, fault detection is important to be include and implement in the process to identify if there is a fault. Basically, there are three methods of fault diagnosis that can be explored which are knowledge-based methods, model-based methods and signal-based methods but the model-based methods had become more useful and popular among three of them as it have been intensively investigated (Wang et al., 2014). To implement model-based methods, mathematical models based on first principle is used as describing normal operating conditions of machines.

2.3 Observer as system fault detection

Generally, fault detection has several significant methods that are based on traditional observer. The observers are design in order to estimate both states and faults. The basics idea about an observer are a dynamic system used to estimate the outputs of the system from the measurements based on measurable system input and output which lead to state observer (Heredia and Ollero, 2009, Lee et al., 2018, Sellami, 2014). This will include a measured feedback signal combining with a mainly the plant followed by the feedback system (Ellis, 2002b). This can be explained by looking to the block diagram as shown in Figure 2.1 below.

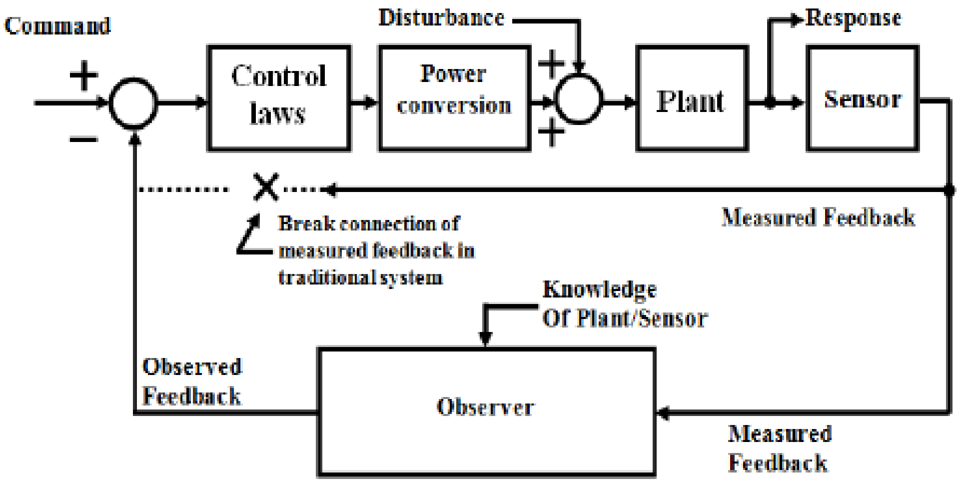

Figure 2.1 – Role of an observer in a control system (Ellis, 2002b)

Thus, the design an observer is based on the estimation process with can be referred to the measured feedback signal with the knowledge of the control system elements. By using the estimation process through model-based methods which are using the mathematical models, the observer can be constructed. But, with the arising issues involving unknown external noises and disturbances that are exist in unpredictable time and surrounding area, the design of control law within the closed loop system will be difficult to build that provide the desired performance. This can lead to several design of observer that will further discussed within next three subsection.

2.3.1 Linear Observer (Luenberger Observer)

Observers have been first designed based on linear system which known as linear observers that used to estimate unknown variable and states in a linear process with the presence of noise or disturbance. To describe the observer equation, the state-space representation is commonly use and the measurement equation is also included in applying a linear model-based observer. Note that the sensitivity of the estimation will be determined by looking to the number of measured variables (Mohd Ali et al., 2015).

The main advantage of conventional linear observers is that the structure is simple and not too complex. Luenberger observers is introduced by the Luenberger who is started the theory of observers that state an observer can be used as long as there is any system driven by the output of given system (Radisavljevic-Gajic, 2014). The main concepts for the Luenberger observer consist of predictor which is a copy of the system is formed and the corrector which indicate the wrong portion in the estimation that is added into the model (Eissa et al., 2015). By considering linear dynamic system,

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{2.1}$$

$$x(t_0) = x_0 = unknown \tag{2.2}$$

$$y(t) = Cx(t) \tag{2.3}$$

where A,B,C are state, input and output matrices that have an appropriate dimensions, and $x(t)$, $u(t)$ and $y(t)$ are the input, state and output vector respectively. The system output variables are available at all times. The dot over a variable refers to the time derivative of the variable. By letting $\hat{x}$ denote the state estimates

$$\dot{\hat{x}} = A\hat{x} + Bu \tag{2.4}$$

$$\hat{x}(t_0) = \hat{x}_0 \tag{2.5}$$

$$\hat{y}(t) = C\hat{x}(t) \tag{2.6}$$

As a result, Luenberger observer equations become as the following

$$\dot{\hat{x}}(t) = A\hat{x}(t) + Bu(t) + L\big(y - C\hat{x}(t)\big) \tag{2.7}$$

From the above equation (2.1) and (2.7), the error can be estimate by using the following formula

$$e(t) = x(t) - \hat{x}(t) \tag{2.8}$$

$$\dot{e}(t) = \dot{x}(t) - \dot{\hat{x}}(t) \tag{2.9}$$

$$\dot{e}(t) = (A - LC)e(t) \tag{2.10}$$

So that the error will decrease over time when using this Luenberger observer. The Figure 2.2 will illustrate on how the process of Luenberger observer will take place in the control system to estimates the state of the output of the system.

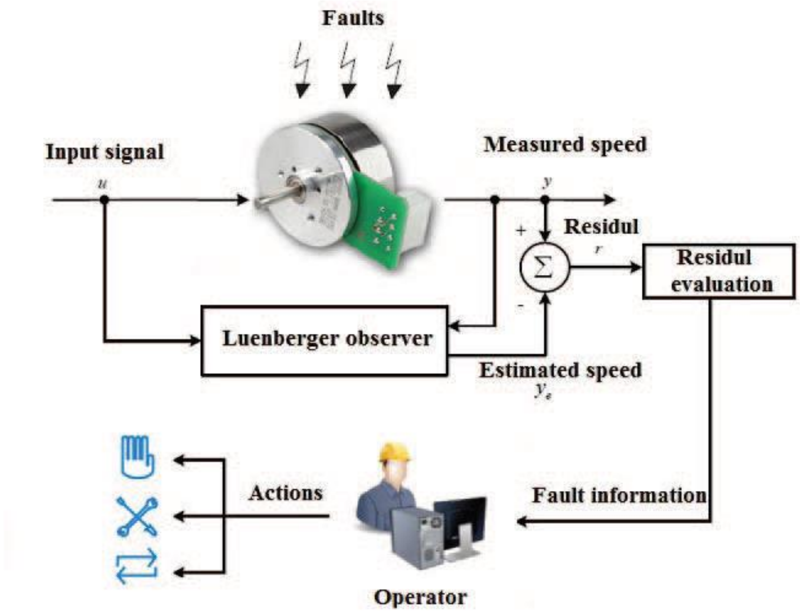

Figure 2.2 – Schematic diagram of observer-based approach for fault detection of DC motor (Eissa et al., 2015)

2.3.2 Adaptive Observer

Adaptive observers design for a linear class of dynamic systems receive considerable attention over the past few years as it been developing in the most of areas of control system theory field. Particularly, adaptive observers design method are based on time-varying system class (Karabutov, 2018). Adaptive observers have the ability of estimating the state with the presence of a disturbance in the system. Unknown parameters that exist in the system is modeled as a function which reflect the disturbance (Rueda-Escobedo and Moreno, 2017). Adaptive observers are widely applied in solving of different state reconstruction problems.

The conventional adaptive observer is constructed and designed as follow

$$\dot{\hat{x}}(t) = A\hat{x}(t) + Bu(t) + E\hat{f}(t) - L\big(\hat{y}(t) - y(t)\big) \tag{2.11}$$

$$\hat{y}(t) = C\hat{x}(t) \tag{2.12}$$

where $\hat{x}(t) \in R^n$ is the observer state vector, $\hat{y}(t) \in R^p$ is the observer output vector and $\hat{f}(t) \in R^r$ is an estimation of actuator fault, $f(t)$. Whilst A, B, C and E are known constant real matrices of appropriate dimensions, and the matrix E is of full column rank and the pair (A,C) is observable. Since the pair (A,C) is observable, the observer gain matrix, L can be selected such that $(A - LC)$ is a stable matrix.

Thus, the error dynamics can be estimated by using the basic formula stated in (2.8) and (2.9) as the following

$$e_x(t) = \hat{x}(t) - x(t) \tag{2.13}$$

$$\dot{e}(t) = \dot{x}(t) - \dot{\hat{x}}(t) \tag{2.14}$$

$$e_f(t) = \hat{f}(t) - f(t) \tag{2.15}$$

$$\dot{e}(t) = (A - LC)e_x(t) + Ee_f(t) \tag{2.16}$$

$$e_y(t) = Ce_x(t) \tag{2.17}$$

As a result, adaptive observer can be designed by using the obtained fault information to eliminate the fault (Zhang et al., 2008). The overview of Model Reference Adaptive System (MRAS) structure can be shown in the Figure 2.3 below.

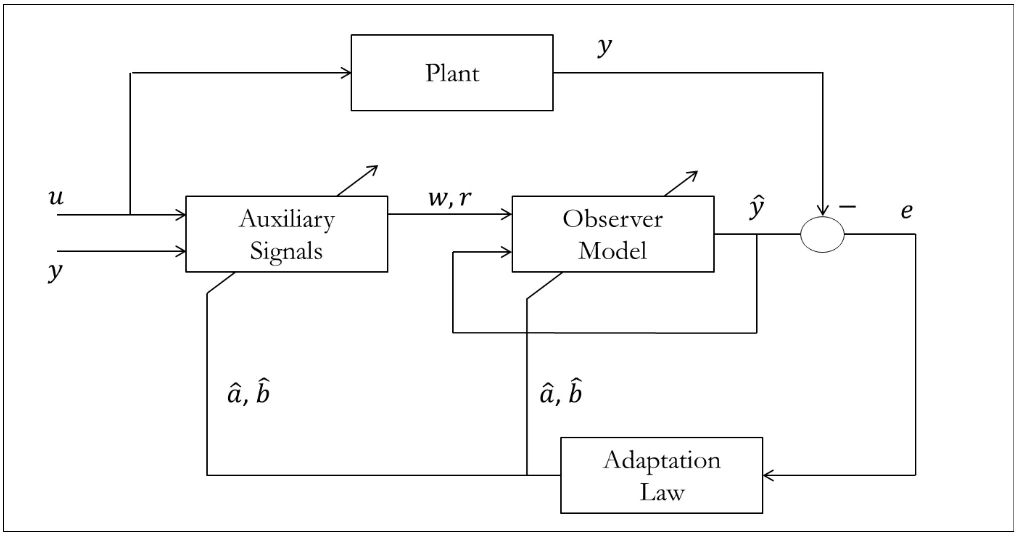

Figure 2.3 – MRAS observer structure

2.3.3 Robust Observer (Sliding Mode Observer)

Sliding mode control is an alternative for making the system more robust with relatively fast transients and attenuate the oscillations. There is a discontinuous function that force the behavior of the system to the sliding surface. The design of sliding mode observer that is not complex but its functional is helpful and effectual make this method is applicable and employed in considerable applications (Zhang and Wang, 2016).

Another element of the sliding mode theory is that the time convergence is finite as well as the accuracy is high which attribute to the robust state estimation. The high gain is needed in sliding mode to make sure the trajectories is reach in finite time which is currently in the presence of unknown inputs and faults. Sliding manifold, S refers to a domain which are initially driven in a finite time or reachability phase and maintained the sliding phase within the closed-loop system dynamics but with a controlled of sliding action. The system needs to be asymptotically stable while on the sliding manifold which the sliding is needed to push the variable towards zero in a finite time. Thus, at the same time the sequential convergence of observation errors tends to converge to zero (Sharma and Aldeen, 2011).

The gain in sliding mode is designed according to the output of the system such that the error is stable in the reaching phase. Most analyses of sliding mode gains are referred to Lyapunov approach which related to the stability of the error dynamics. When the sliding mode is maintained and sliding surface is approached, the system behavior will be alike to that of a reduced-order system. A non-linear system is assumed as follows

$$\dot{x} = Ax + \Phi(x,u) + E(x,u)f(t) \tag{2.18}$$

$$y = Cx \tag{2.19}$$

where $A \in R^{n\times n}$, $C \in R^{p\times n}$ with $m < p \leq n$, $x \in M \subset R^n$ is the state vector, $u \in U \subset R^q$ (U is an admissible control set) are the bounded control inputs, $y \in Y \subset R^p$ (Y is the output space) are the system outputs, the unknown functions

$$f(t) = [f_1(t) \quad f_2(t) \quad \dots \quad f_m(t)] \in R^m$$

are the faults or unknown inputs and are assumed to be bounded as $\|f(t)\| \leq \bar{f}$, $\Phi(x, u)$ is a real valued vector field on R^{n+q} and $E(x, u)$ is an $n \times m$–matrix with real value functions on R^{n+q}.

The observability and controllability test must be performed first before commencing the sliding mode observer design. After those test is satisfy, an observer of the following form can be designed to estimate the states

$$\dot{\hat{x}}(t) = A\hat{x} + \Phi(\hat{x}, u) + L(y - C\hat{x}) + E(\hat{x}, u)v(t) \qquad (2.20)$$

where L is the feedback gain and $v(t)$ is the robust term given by the sliding mode estimation

$$v(t) = -\left(C_1 E(\hat{x}, u)\right)^{-1} \rho(.) sign(C_1\hat{x} - C_1 x) \qquad (2.21)$$

where $\rho(.)$ is a positive scalar function to be determined.

Based on the basic formula stated in (2.8) and (2.9) before, the estimation of error dynamics can be deduced as

$$\dot{e} = (A - LC)e + \Phi(\hat{x}, u) - \Phi(x, u) + E(\hat{x}, u)v(t) - E(x, u)f(t) \quad (2.22)$$

As the non-linear matrix $E(.)$ and faults $f(t)$ are bounded, the boundedness of the error dynamics can be set with a proper selection of feedback gain, L by referred to theory of Lyapunov (Veluvolu and Soh, 2011).

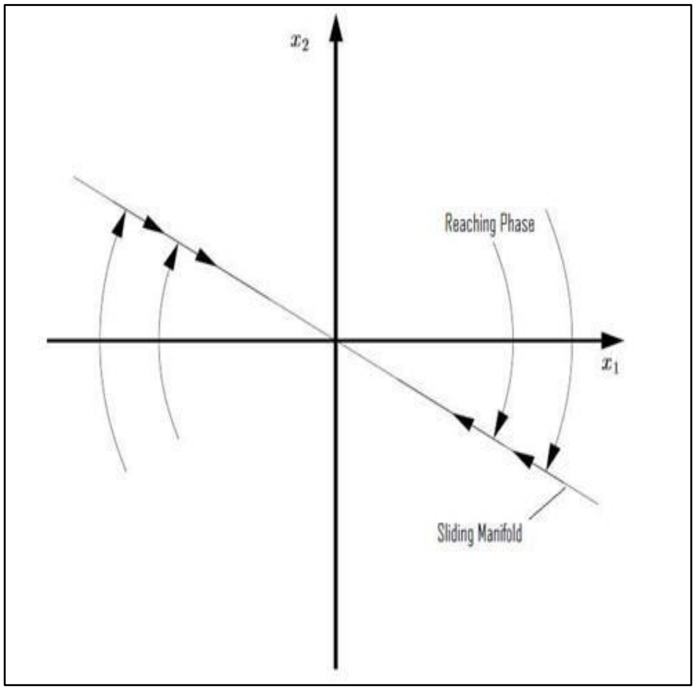

Figure 2.4 – A typical phase portrait under sliding mode control (Ehsan)

2.4 Other fault detection method

Others than Luenberger observer, adaptive observer and sliding mode observer that had been discussed on previous section, there are some approaches that can be used to detect the faulty system or subsystem. One of the method is via Takagi-Sugeno (T-S) fuzzy models. This fuzzy system is capable in approximating any smooth non-linear systems to any specified accuracy within any compact set through fuzzy membership functions of local linear models. Many complex nonlinear system can be considered based on this local linearity through T-S fuzzy models. Simple view about this fuzzy model can be illustrated in the Figure 2.5 below. The concept is same which the dynamic system whose contain the information of physical plant is constructed in which the residual signal is generated in order to decide if the fault is occurred or not. The process involved consist of two main things. First, a residual signal, r(k) is generated and the filter is designed to make the overall fault detection system is exponentially mean square stable with the following auxiliary H_∞ performance constraint with zero initial condition.

Second, the fault detection is measure with adoption of a residual evaluation stage (Dong et al., 2012).

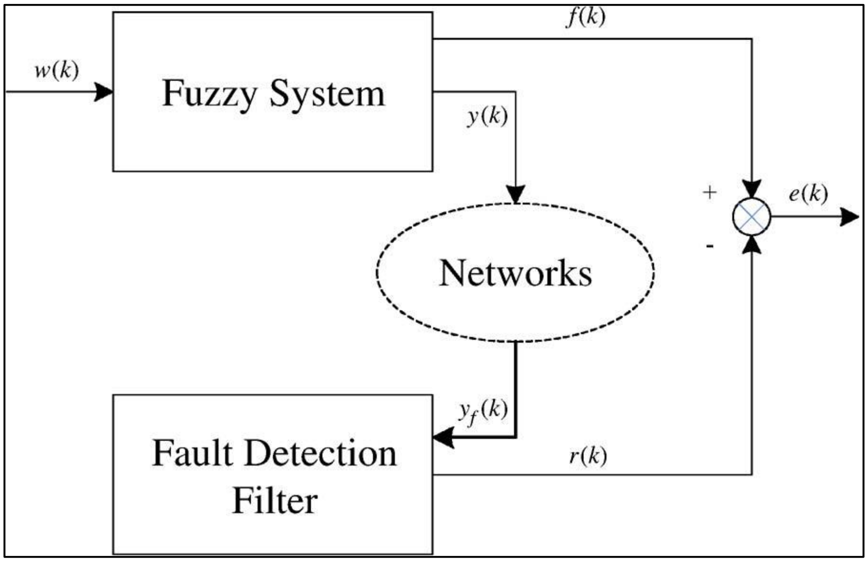

Figure 2.5 – Framework of the fuzzy fault detection filter design over network environments (Dong et al., 2012)

There is another fault detection method which are using fault tree analysis (FTA). This method has been practically used in many applications which involves complex diagnostic such as flight control system and spacecraft propulsion system. FTA is the shortest way to find a fault or diagnosis a fault in a complex machinery. There are several process involve in FTA in order to do the fault diagnosis. This can be referred to Figure 2.6 below which lists the process from beginning to the final stage. FTA is a fault diagnosis approach that implements to detect the causes of the system failure via hierarchy from the system level to part stages. This method is selected in the field of manufacturing system as it analyses a specific fault level by level, indicating a system fault which is related to which parts according to the fault tree. Such approach allow designers to be certain of the fault modes and success modes of the system through qualitative analysis of fault trees of a system (Hu et al., 2003).

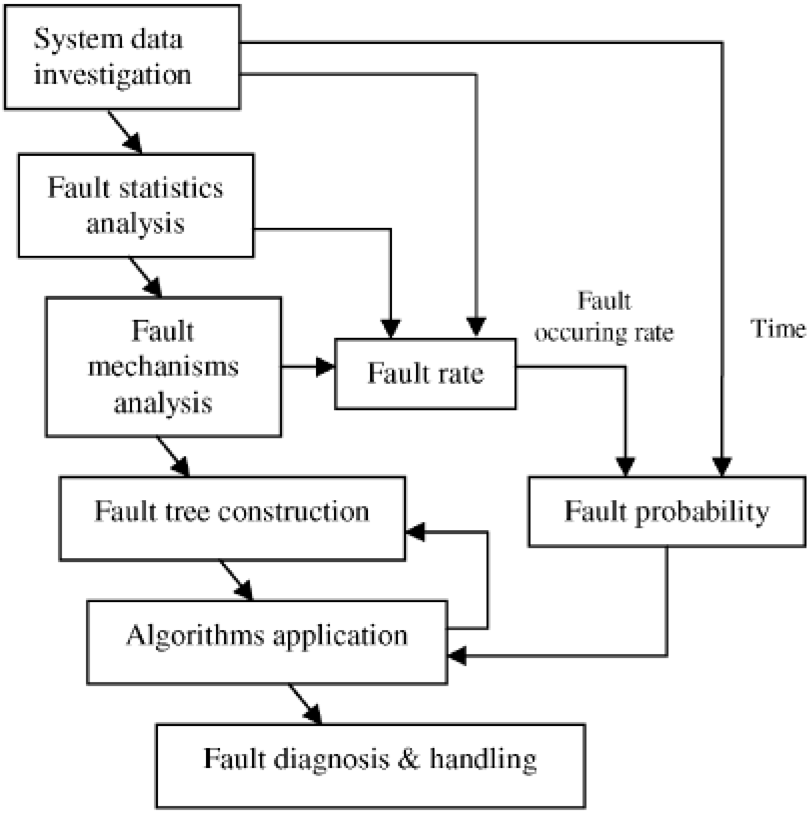

Figure 2.6 – The process of FTA (Hu et al., 2003)

Actually, there are others fault detection methods besides those two aforementioned above which can be simplified into a few categories which are classical method, wavelet transform and finite element method (FEM), artificial intelligence (AI) techniques and numerical and experimental techniques. These categories, proposed by (Thatoi et al., 2012) are used for fault diagnosis which specify cracked structures and condition monitoring of machines and structural systems. Besides that, there is another method that is presented by Pandalai and Halloway (2000) which depends on the basis of event order and timed behavior of a system. Condition template is used instead of state estimation within this method which analyses the system by creating events with the right order or in the given time delays. Should there be anything wrong about its reaction in the process, a fault can be preemptively detected (Roth et al., 2012).

2.5 Observer versus other fault detection method

Each of the method has their own advantages and disadvantages but their main purpose is to determine and give the signal if the fault occur anywhere in the system (Gertler, 2015). We can estimate when the system is defined as a faulty system and make a preparation to overcome that problems. But, their approaches to detect the fault of the system are not the same like an observer that use a state equation by considering a dynamic system (Eissa et al., 2015, Zhang et al., 2008, Veluvolu and Soh, 2011) and fault free analysis (FTA) use several stages including algorithm (Hu et al., 2003).

2.6 Summary

In order to avoid some system from becoming faulty condition, another approach need to be taken and implemented in the system. Based on the investigated literature review, the important of fault detection has attracted many researchers to find alternative method to solve this problem as it will affect the performance of the whole system. Hence, the observer method has been introduced to be designed as it suitable in fault detection in a dynamical system. As mentioned before, linear observer is useful when involving the linear system and without having the presence of disturbance and noise in the system. While, adaptive observer is to be employed whether the class of the system is linear or nonlinear and can adapt with the estimation of the state even though in the presence of disturbance that exist in the system. For sliding mode observer, it is more robust and fast to reconstruct back the signal.

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this chapter, the method use for fault detection will be explained through its design which included linear observer and sliding mode observer that tested via simulation for both method and via hardware for sliding mode observer only. In the beginning, the design of linear observer (Luenberger observer) will be discussed in section 3.2. This will be followed by the design of sliding mode observer which discussed in section 3.3. The dynamic modelling of DC motor will be presented in section 3.4. The hardware part which covered the DC motor, a concept of an encoder, the selection of Arduino Mega 2560 and L293D motor driver IC will be discussed in section 3.5. For the software part, it will cover on design of linear observer (Luenberger observer) via simulation and sliding mode observer via simulation and experimental which will be represented in section 3.6.

3.2 Linear Observer (Luenberger Observer) design

Through this project, the system was ran into two different environment which consist of the system with a noise present and without the present of noise within the system.

For the system without the present of noise, consider the system is described by

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{3.1}$$

$$y(t) = Cx(t) \tag{3.2}$$

with the input $u(t) \in \Re^{r}$, the state $x(t) \in \Re^{n}$ and the output $y(t) \in \Re^{m}$ where $\Re$ denotes the real number of vector and $A \in \Re^{n\times n}$, $B \in \Re^{n\times r}$ and $C \in \Re^{m\times n}$ is in the matrices form of actual plant.

While, for the system with the present of noise, the equation (3.2) above will become as follow:

$$y(t) = Cx(t) + N_o(t) \tag{3.3}$$

where N_0 is present as external noise (Band-Limited White Noise via Simulink MATLAB software platform). The reason this external noise is put on the output equation is because of the objective of this project which want to detect the fault at the output (sensor) only. So, by doing this, the external noise will affect the output reading from the sensor itself which for this project, an encoder is used to read the position value and will produce the corrupted position reading.

The Luenberger observer is designed as follows

$$\dot{\hat{x}}(t) = A\hat{x}(t) + Bu(t) + L[y(t) - C\hat{x}(t)] \tag{3.4}$$

$$\hat{y}(t) = C\hat{x}(t) \tag{3.5}$$

where $\hat{x}$ and $\hat{y}$ are the estimated system state and output respectively. L is refer to the observer gain which is designed to provide the required performance of the observer. To solve the observer gain, L, the ackermann's rule is implemented.

For the state estimation error, $\dot{e}$ can be calculated as

$$e(t) = x(t) - \hat{x}(t) \tag{3.6}$$

$$\dot{e}(t) = \dot{x}(t) - \dot{\hat{x}}(t) = (A - LC)e(t) \tag{3.7}$$

Now, choose the value of L such that the eigenvalues of $(A - LC)$ can be arbitrarily placed in the complex plane which guarantees the observer errors to converge to zero for any initial conditions. But, the state equation must be controllable and observable. This can be test via controllability test and observability test. Observability is the ability to place the eigenvalues of $(A - LC)$ arbitrarily by using L. The observability matrix, O is defined as

$$O = \begin{bmatrix} C \\ CA \\ CA^2 \\ \vdots \\ . \\ CA^{n-1} \end{bmatrix}$$

If the rank is equal to dimension of the A matrix, the system is observable. Controllability matrix C remains the same and replace A' with A and B' with C to get O. This can be easily done with using MATLAB command to get both observability and controllability which are obsv(A,C) and ctrb(A,B) respectively. From here, the gain, L is identified which using MATLAB command L=acker (A', C', pe) which pe is referred to the vector of desired poles.

3.2.1 State-Space Model

In the state-space form, the current, i, the angular position, θ and the angular speed, $\dot{\theta}$ is chosen as the state variables. The armature voltage is selected as the input while the angular position is chosen as the output. The dynamic equations in state-space form are as the following

$$\frac{d}{dt}\begin{bmatrix} i \\ \theta \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} -R/L & 0 & -Ke/L \\ 0 & 0 & 1 \\ Ke/J & 0 & -b/J \end{bmatrix}\begin{bmatrix} i \\ \theta \\ \dot{\theta} \end{bmatrix} + \begin{bmatrix} 1/L \\ 0 \\ 0 \end{bmatrix} V$$

$$y = \begin{bmatrix} 0 & 1 & 0 \end{bmatrix}\begin{bmatrix} i \\ \theta \\ \dot{\theta} \end{bmatrix}$$

Based on equation (3.8) and (3.9), the A, B, C and D matrices can be determined and stated as follows

$$A = \begin{bmatrix} -R/L & 0 & -Ke/L \\ 0 & 0 & 1 \\ Ke/J & 0 & -b/J \end{bmatrix}$$

$$B = \begin{bmatrix} 1/L \\ 0 \\ 0 \end{bmatrix}$$

$$C = \begin{bmatrix} 0 & 1 & 0 \end{bmatrix}$$

$$D = 0$$

The value of 1 on C matrix is indicated that the output will give the reading of angular position because of the selected encoder that attached together with DC motor is reading the position value.

3.3 Sliding Mode Observer (Robust Observer) design

A robust observer is to be design to detect faults of the encoder attaches to a DC motor which is the actuator of the robot arm.

Let the state-space representation of the DC motor be define as follows:

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{3.8}$$

$$y(t) = Cx(t) \tag{3.9}$$

where A ∈ $\Re^{n \times n}$ system matrix, x ∈ $\Re^{n}$ system state, B ∈ $\Re^{n \times m}$ input matrix, u ∈ $\Re^{m}$ control input signal, y ∈ $\Re^{p \times n}$ output of the system and C ∈ $\Re^{p \times n}$.

To allow the output of the system be transformed as system state components, a change of coordinates ought to be done. Let,

$$T_c = \begin{bmatrix} N_c^T \\ C \end{bmatrix} = \begin{bmatrix} -1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \tag{3.10}$$

where Nc ∈ $\Re^{n \times (n-p)}$ span the null space of C. Therefore, the resulting nonsingular transformation matrix for the output,

$$CTc^{-1} = [0 \quad Ip] = [0 \quad 0 \quad 1]$$

The subsequent transformation imposed on the system matrix and input matrix can be defined as follows:

$$T_cAcT^{-1} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \quad \text{and} \quad T_cB = \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} \tag{3.11}$$

where $A_{11} = 1 \times 10^3 \begin{bmatrix} -1 & 0.1 \\ -0.02 & 0 \end{bmatrix}$; $A_{12} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$; $A_{21} = [0 \quad 1]$; $A_{22} = [0]$ and

$B_1 = \begin{bmatrix} -1000 \\ 0 \end{bmatrix}$; $B_2 = [0]$

Now, we are able to pursue for the robust observer design using the following transformed nominal system,

$$\dot{x_1}(t) = A_{11}x_1(t) + A_{12}y(t) + B_1u(t) \tag{3.12}$$

$$\dot{y}(t) = A_{21}x_1(t) + A_{22}y(t) + B_2u(t) \tag{3.13}$$

Noting that, $T_cx = [x_1 \quad y]^T$

But, when there is a faults present in the output which refer to encoder position reading, the linear system is considered as

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{3.14}$$

$$y(t) = Cx(t) + f_o(t) \tag{3.15}$$

where $f_o(t)$ is deemed to represent sensor faults (encoder faults for this project).

To synthesise an observer to generate a state estimate $\hat{x}(t)$, the sliding mode is established in which the output error is forced to zero in finite time.

$$e_y(t) = \hat{y}(t) - y(t) \tag{3.16}$$

Then, the sliding mode observer structure is

$$\dot{\hat{x}}(t) = A\hat{x}(t) + Bu(t) - G_l e_y(t) + G_n v \tag{3.17}$$

$$\hat{y}(t) = \hat{x}(t) \tag{3.18}$$

where the linear gain

$$G_l = Tc^{-1}\begin{bmatrix} A_{12} \\ A_{22} - A_{22}^s \end{bmatrix} \tag{3.19}$$

the nonlinear gain

$$G_n = Tc^{-1}\begin{bmatrix} 0 \\ I_p \end{bmatrix} \tag{3.20}$$

the discontinuous vector

$$v = -\rho \frac{P_2 e_y}{0.01 + \|P_2 e_y\|} \tag{3.21}$$

and A_{22}^s is a stable design matrix, ρ is scalar function and P$_2$ ∈ $\Re^{p \times p}$ is symmetric positive definite Lyapunov matrix for A_{22}^s.

3.4 Dynamic Modelling

In this section, the dynamic modelling of DC motor was presented which covered of its system equation and its transfer function.

3.4.1 System Equation

Generally, a DC motor will produce the torque that is proportional to the armature current and the strength of the magnetic field. By assuming the magnetic field is constant, then the motor torque is proportional to only armature current, *i* by a constant factor, K_t. This is referred to as an armature-controlled motor.

$$T = K_t i \tag{3.22}$$

Then, the back emf, *e* is proportional to the angular speed of the shaft by a constant factor, K_e

$$e = K_e \dot{\theta} \tag{3.23}$$

But, for motor torque constant, K_t and electromotive force constant, K_e, its SI units are equal. Hence, *K* is used to represent both motor torque constant and electromotive force constant.

From Figure 3.1, the following equation can be derive by using Newton's 2nd law and Kirchhoff's voltage law.

$$J\ddot{\theta} + b\dot{\theta} = Ki \tag{3.24}$$

$$L\frac{di}{dt} + Ri = V - K\dot{\theta} \tag{3.25}$$

3.4.2 Transfer Function

After the above equation has been derived, the modelling equations can be expressed in terms of Laplace variable, *s* by applying the Laplace transform.

$$s(Js + b)\Theta(s) = KI(s) \tag{3.26}$$

$$(Ls + R)I(s) = V(s) - Ks\Theta(s) \tag{3.27}$$

The equations (3.26) and (3.27) are needed to obtain the transfer function in (3.28) by eliminating I(s) in those two equation where the angular speed is considered as the output and the armature voltage is considered as the input.

$$P(s) = \frac{\dot{\Theta}(s)}{V(s)} = \frac{K}{(Js+b)(Ls+R)+K^2} \quad \left[\frac{rad/sec}{V}\right] \tag{3.28}$$

3.5 Hardware Platform

A several part or component had been chosen and selected for this research of works. Mainly, the DC motor that attached with an encoder is work as a plant that can be measured of its faulty dynamic system. The encoder is act as a sensor that read the number of pulses and converted to the angular position by using the formula that will mentioned in this subsection later. Next, the Arduino MEGA 2560 is used to interface between the DC motor with an encoder and the Simulink MATLAB. Finally, L293D is used to drive the DC motor which is then an encoder will rotated eventually.

3.5.1 DC Motor

The most common device used as an actuator in mechanical control is the DC motor. Despite of that, the DC motor is a suitable device to be used to investigate its performance when it working in the uncertainty environment as it receive a lot of disturbance during operation. Taking a DC motor as the research subject, its physical characteristics and system equation must be discovered so that its mathematical modelling can be model.

3.5.1.1 Physical Setup

A DC motor directly provides rotary motion and coupled with wheels or drums and cables, and also can provide translational motion. The equations defining a DC motor motion can be expressed in both mechanical and electrical ways. A simple overview on electrical equivalent circuit of the armature and the free body diagram of the rotor are shown in Figure 3.1.