Robust Fault Tolerant Control of an Unmanned Aerial Vehicle in the Presence of Actuator Faults

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Declaration

I certify that this research work titled "*Robust Fault Tolerant Control of an Unmanned Aerial Vehicle in the Presence of Actuator Faults*" is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged / referred.

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Language Correctness Certificate

This thesis has been read by an English expert and is free of typing, syntax, semantic, grammatical and spelling mistakes. Thesis is also according to the format given by the university.

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Copyright Statement

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Dedicated to my beloved parents, esteemed teachers, much-loved siblings and sincere friends, without you all, life is meaningless.

Abstract

The control and navigation of Unmanned Aerial Vehicles (UAVs) is quite demanding in general as these autonomous vehicles experiences different kind of faults during flight. Successful flight of UAVs hence demands some methods or techniques by virtue of which these autonomous vehicles can cater for these faults and deal with them efficiently as early as possible. Many different schemes have been developed for the Fault Tolerant Control (FTC) of UAVs. In this study, a robust approach for the FTC of a UAV in the occurrence of three different forms of actuator faults namely abrupt, incipient and intermittent is developed and verified. The Fault Detection and Isolation (FDI) is achieved by employing the Observer based residual scheme. In order to make the generated residuals insensitive to disturbances and uncertainties, the method of Eigenstructure Assignment (EA) is also incorporated in the FDI scheme. The Sequential Probability Ratio Test (SPRT) is employed for the efficient statistical testing of the residuals during the detection phase. Afterwards the Multiple Models Switching and Tuning (MMST) technique based on Linear Quadratic Gaussian Regulator (LQG) is designed and used as the reconfigurable controller. A linearized lateral directional model of the Aerosonde UAV is then used to test the robustness and efficacy of the proposed scheme for FTC in Simulink (MATLAB). The results of the simulations duly justify the efficiency of the developed FTC scheme for a UAV. The proposed FTC scheme is hence an efficient, robust and practical methodology for the detection and reconfiguration of the actuator faults occurring in UAVs during flight.

Key Words: *Unmanned Aerial Vehicle, Fault tolerant control, Actuator, Fault detection and isolation, Observers, Eigenstructure assignment, Linear Quadratic Gaussian, Robustness, Redundancy, Eigenvalues*

Table of Contents

List of Figures

List of Tables

CHAPTER 1: INTRODUCTION

This chapter serves to introduce the main inspiration, aims and scope of the research. The requirements which led to the formulation of the FTC technique for UAVs are also discussed in this chapter. At the end, an outline of the thesis and its organization is provided.

1.1 Motivation

Unmanned Aerial Vehicle (UAV)-as the name implies- is an aircraft without any human pilot on board. UAVs can either be remotely controlled or autonomous. The earliest UAVs were developed and used primarily for military purposes in the mid-1800s [1]. Today, UAVs are being used for different applications; military, remote sensing, aerial surveillance, photography and filming, oil and gas exploration, disaster relief, scientific research, to name a few. The use of UAVs for accomplishing different tasks in the current era has made the design, control and navigation of these autonomous vehicles an active area of study and research. The control and navigation of UAVs is quite a challenging task generally and it requires a great amount of research and effort to operate a UAV safely and efficiently to get the desired response since these systems are generally quite vulnerable to various faults during operations. During flight, UAVs may experience different faults which have to be dealt with as early as possible since they may cause undesirable behaviour or even closed loop instabilities which may prove to be disastrous for the UAVs. Around 80 percent of the incidents of failures occurring in UAVs are basically due to the faults occurring in the UAV’s actuators, sensors or control surfaces as per a survey by the US Office of the Secretary of Defence [2]. Hence different techniques for the FTC of UAVs have been developed and employed to deal with such faults and improve the reliability and life time of UAVs.

The main idea which served as a motivation for this research work was to develop a robust technique which would help the UAVs cater for the actuator faults experienced during flight efficiently.

1.2 Problem Statement

The FTC of UAVs is important for their safe operation in practical environments due to the presence of faults. The core objective of this thesis is "to develop a robust FTC approach for UAVs for dealing with the actuator faults occurring during flight." For this purpose, this research uses the observer based residual generation method and the residuals are made insensitive to uncertainties and noise disturbances through the Eigenstructure Assignment method. SPRT is then employed for fault detection and subsequently the LQG based MMST technique is developed for the reconfiguration phase.

1.3 Requirements and Research Approach

During flight, UAVs experience different types of actuator faults which might affect their stability and overall performance. To alleviate the effects of such faults, the FTC scheme developed has to be efficient, swift and robust to the disturbances and uncertainties present in the environment. Various FTC techniques were discussed and planned in the initial phase of this research. These FTC methods were analysed on the basis of complexity, efficiency and robustness to environmental disturbances and uncertainties. Due to the reduced complexity and overall performance, the full-state observer method was selected for the purpose of generating residuals during the fault detection stage. The residual generation method on testing, worked very well for the case where no disturbances and uncertainties were present in the system but it could not detect actuator faults accurately when noise disturbances and uncertainties were introduced in the system. Since in most practical applications, the environment faced by UAVs is corrupted by noise and there are model uncertainties present in the system, so a full-state observer residual generation method was not adequate enough on its own to detect the actuator faults. Due to this reason, different methods to make the residuals robust to the disturbances were researched upon and a mathematical method known as "Eigenstructure assignment" was selected for the robustness of the residuals.

After the residual generation, the problem of detection of the actuator faults at the earliest was studied. The Sequential Probability Ratio Test (SPRT) method was selected which proved to be very efficient in detecting actuator faults upon testing. A lot of study had to be done in selecting the parameters for the SPRT which produced the desired results for fault detection.

Once the techniques were finalized for the fault detection stage, the focus of the research was then shifted towards the appropriate reconfiguration action which would ensure the stability of the UAV system. Several methods were researched upon for this and finally the technique known as Multiple Models Switching and Tuning (MMST) was chosen for the reconfiguration stage. In order to make the reconfiguration step optimal and efficient, Linear Quadratic Gaussian (LQG) regulators were based MMST design was decided upon and developed.

After the research and development of the FTC technique, the next step undertaken was to study and analyse the UAV model that would be used for the purpose of simulations and testing of our FTC method. For this purpose, first of all a brief study of the UAV aerodynamics was conducted to better understand the mathematical modelling. The various kinds of faults occurring in the UAVs were studied along with the types of noise and disturbances encountered by UAVs during flight in practical environments. Actuator faults of three different types were then used along with Gaussian noise disturbances for simulations. Next, a decision was made whether to use a linear or a non-linear model of UAV for the simulations and testing phase for which an analysis of the different existing UAV state-space models was made. Once it was settled that the state space model of the UAV used would be linear, different accessible linearized state space models of UAVs were thoroughly studied and analysed. A linearized lateral directional model of the Aerosonde UAV was finally selected and used for the simulations and testing of the developed FTC technique.

The aforementioned technique developed for the Fault Tolerant Control of UAVs was tested and it proved to be quite effective and robust against disturbances in the event of actuator faults.

1.4 Scope of the Thesis

The research work put forth in this thesis deals with the design and development of a robust FTC technique for UAVs in the presence of different kinds of actuator faults. The aspects that were looked into for the purpose of this research work were the development of a fault detection scheme that was robust to the noise and disturbances present in the environment and a reconfiguration method that allowed the UAV to cater for the actuator faults efficiently and stably. The linearized lateral directional model of the Aerosonde UAV was later on used as a tool for testing the developed FTC technique and analysing its performance.

1.5 Thesis Outline

The following chart sums up the organization and outline of our thesis:

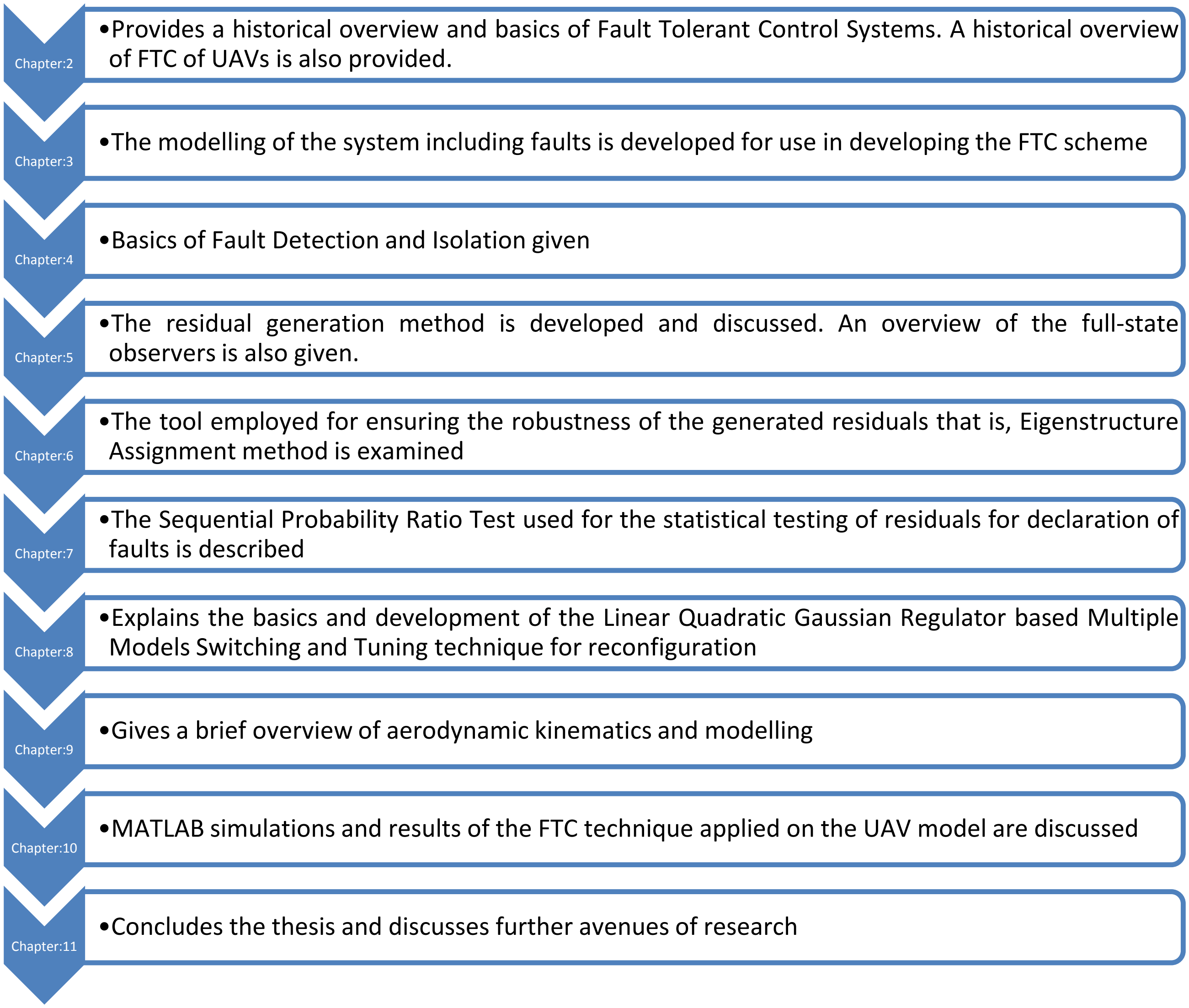

Figure 1.1: Organizational chart of the thesis

CHAPTER 2: OVERVIEW AND ANALYSIS OF FTC

This chapter provides the literature review of FTC. A historical overview of the developments made in the realm of FTC is presented. The common terminology used and the basic concepts of FTC are also discussed. A brief summary of the research and work done on the FTC of UAVs to date is also made a part of this chapter.

2.1 FTC Systems-A Historical Overview

The theory of FTC was basically born when Neumann suggested the concept of duplication to improve the safety and reliability of systems in the year 1956 [3]. To reduce the costs, replacing hardware redundancy by analytical for FTC was proposed by Beard in 1971 at MIT through the use of fault detection filters [4]. The development of different FDI and FTC techniques over the years has been discussed in various publications some of which are illustrated in a chronological order in Table 2-1.

Table 2-1: Chronological classification of FDI and FTC methods

Year	**FDI Methods**	**FTC Methods**
1971	[4], [5]	
1974	[6], [7]	
1975	[8]	
1979	[9]	
1980	[10]	
1981	[11]	
1982	[12], [13]	
1986	[14], [15]	
1987	[16]	
1988	[17], [18]	
1989	[19]	
1991	[20]-[22]	[23]
1992	[24]	

1994	[25]	
1997	[26]	[27], [28]
2005	[29]	[30]
2006	[31]	
2008	[32]	[33], [34]
2009		[35]
2010		[36], [37]
2011	[38]	
2012	[39]-[41]	[42]- [44]
2013	[45], [46]	[47], [48]
2014	[49]	[50]
2015	[51], [52]	[53], [54]

Since the early days of conception, the method of FTC has gained popularity and has been employed for the safety and reliability of many critical systems and applications such as nuclear power plants [55] - [57], automotive systems [58], chemical processes [59], [60] and aerospace systems [61]-[64].

2.2 Basics of FTC

2.2.1 Terminology used for FTC

The International Federation of Automatic Control (IFAC) SAFEPROCESS Technical Committee has tried to define the basic terms used in the theory of FTC [65]. Some of the terms and their definitions are stated in [66], [67]. The terms which are useful for the comprehension and development of this research are given below:

Fault:

An unpermitted deviation of at least one characteristic property or parameter of the system from the acceptable, usual or standard condition.

Failure:

A permanent interruption of a system's ability to perform a required function under specified operating conditions.

Malfunction:

An intermittent irregularity in the fulfilment of a system's desired function.

Disturbance:

An unknown (and uncontrolled) input acting on a system.

Residual:

A fault indicator, based on a deviation between measurements and model-equation-based computations.

Fault detection:

Determination of faults present in a system and the time of detection.

Fault isolation:

Determination of the kind, location and time of detection of a fault. Follows fault detection.

Fault identification:

Determination of the size and time-variant behaviour of a fault. Follows fault isolation.

Fault diagnosis:

Determination of the kind, size, location and time of detection of a fault. Follows fault detection. Includes fault detection and identification.

Protection:

Means by which a potentially dangerous behaviour of the system is suppressed if possible, or means by which the consequences of a dangerous behaviour are avoided.

Quantitative model:

Use of static and dynamic relations among system variables and parameters in order to describe a system's behaviour in quantitative mathematical terms.

Analytical Redundancy:

Use of more (not necessarily identical) ways to determine a variable, where one way uses a mathematical process model in analytical form.

Reliability:

Ability of a system to perform a required function under stated conditions, within a given scope, during a given period of time.

Safety:

Ability of a system not to cause danger to persons or equipment or the environment.

2.2.2 Types of faults

Faults can be categorised according to their place of occurrence, their time dependency or with regards to process models. If the classification is based off on the location of occurrence then the faults are of the following three types [68]:

Actuator fault:

In a control system, actuators are the elements that control or actuate the plant by getting activated. So actuator faults and malfunctions can lead to a partial or complete loss of system functions and dynamics and ultimately cause the failure of the control system. Actuator faults are of different types namely hard over, float, lock-in place and loss of effectiveness [69].

Sensor fault:

Sensor faults appear as errors in the measurements of the process variables made in the control system. The different types of sensor faults are: loss of accuracy, drift, bias, and freezing and calibration error.

Component fault:

Component faults affect and change the dynamics of the control system. This may lead to invalid dynamics between the varying physical variables of the system.

Based on their time dependency, the following faults may be experienced by any system [66], [67]:

Abrupt fault:

Fault modelled as stepwise function. It symbolises a bias in the monitored signal.

Incipient fault:

Fault modelled by means of ramp signals. It symbolises a drift of the monitored signal.

Intermittent fault:

Combination of impulses of faults which can have different amplitudes and occur in a periodic manner with a specific time period.

Generally, incipient and intermittent faults are tougher to detect as compared to abrupt faults.

With regards to process models, a fault can be of the following types:

Additive fault:

Influences a variable by an addition of the fault itself. They may represent, e.g., offsets of sensors.

Multiplicative fault:

Is represented by the product of a variable with the fault itself. Can act as parameter changes within a process.

2.2.3 An overview of FTC

Fault tolerance is actually the "the ability of a controlled system to maintain control objectives, despite the occurrence of a fault. A degradation of control performance may be accepted. Fault-tolerance can be obtained through fault accommodation or through system and /or controller reconfiguration" [70]. Fault Tolerant Control is basically a control methodology which persistently allows the safe running of a control process along with assisting in providing acceptable deviations of the control process whenever a fault occurs. A great amount of study and developments on FTC have been carried out in the past and it is an ever-growing arena of research to date also. The control systems which possess the ability to detect and cater for the effects of faults are known as Fault Tolerant Control Systems (FTCS). According to the Zhang and Jiang: "control systems which enjoy the capability to accommodate component failures automatically. They are capable of maintaining overall system stability and acceptable performance in the event of such failures. In other words, a closed-loop control system which can tolerate component malfunctions, while maintaining desirable performance and stability properties is said to be a fault-tolerant control system" [34]. This makes FTC an important and essential component of many critical systems today.

Three different but important areas of control systems; FDI, reconfigurable control and robust control, contribute together to form the vast field of FTC. Each of these fields is a separate area of research in itself. The interaction of the above mentioned elements of FTC is depicted in Figure 2.1 [69]. The various areas are discussed separately and elaborately by Patton in [27].

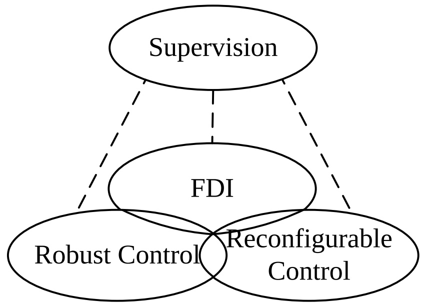

Figure 2.1: The areas of FTC [27]

FTC is divided into two main groups; active FTC and passive FTC (Figure 2.2), each of which is described below [27], [34]:

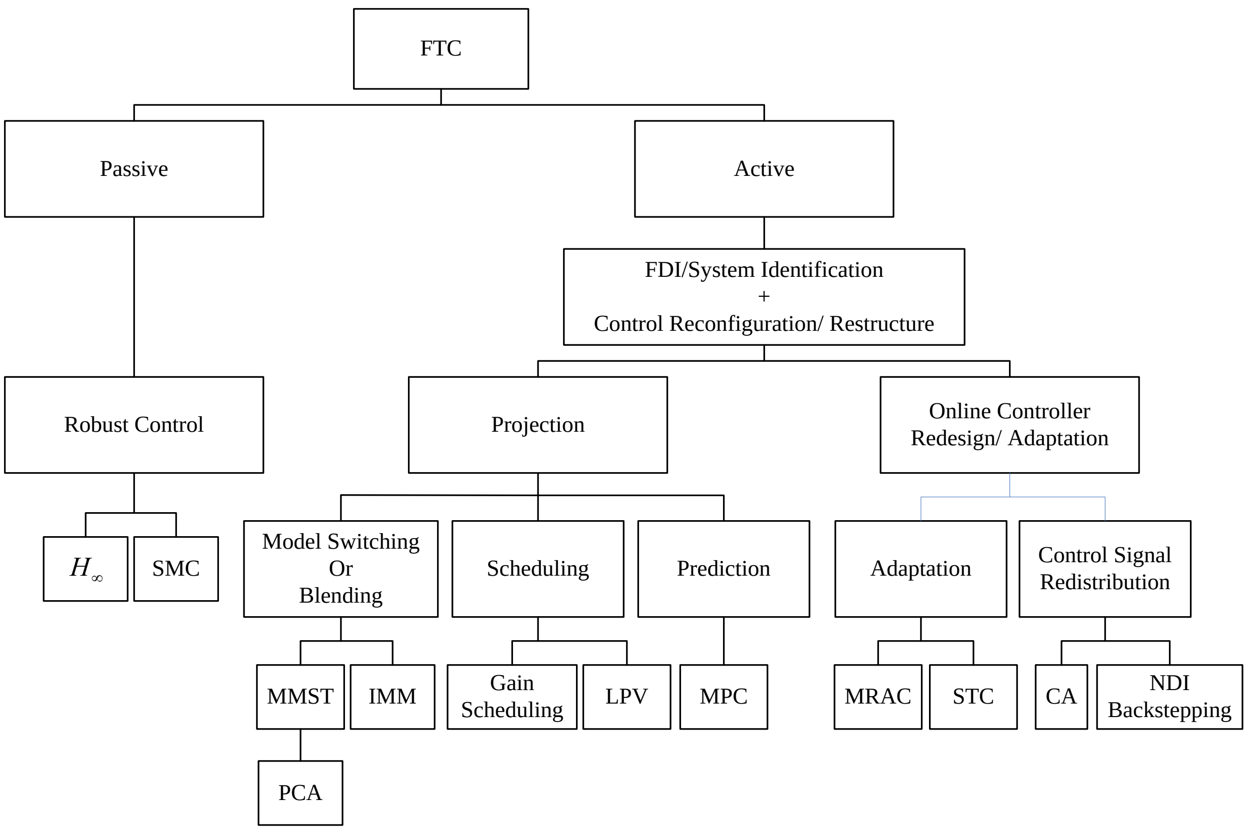

Figure 2.2: FTC classification [27]

Active FTC:

This type of FTC is "active"- as the name suggests. It responds to the faults intelligently by redesigning a new control system to safeguard the overall stability and performance of the control system at an adequate (reduced) level. Active FTC (AFTC) requires some means or methodology by which prior knowledge of the faults be made available to the reconfiguration mechanism. Either the type of fault most likely to affect should be known beforehand or some fault detection scheme should be present in an active FTCS. Therefore the active type of FTC has an FDI section which provides the necessary and requisite information regarding faults. AFTC is further classified into projection type FTC and online redesign or adaptation type. In the projection type AFTC, an appropriate control-law is selected depending upon the faults with the control-law being pre-designed. Projection type FTC has three further categories; scheduling, prediction and model switching or blending. On the other hand, in the online redesign/ adaptation type of AFTC, a new control-law is calculated after the occurrence of a fault, this is called reconfiguration. AFTC may also include fault identification or fault diagnosis schemes instead of an FDI scheme. The general scheme of AFTC is shown in the following figure.

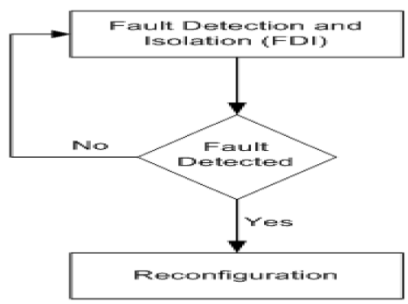

Figure 2.3: The general FTC scheme

Passive FTC:

Passive type of FTC is mostly based on the approaches of robust control and it does not require any information regarding the faults. The controller and the system structure remains fixed in passive FTC (PFTC) hence the original system's performance is retained. In most practical scenarios however, AFTC is preferable as compared to PFTC as the information regarding faults is usually necessary for any reconfiguration action to take place. More information regarding PFTC can be obtained from [71].

The design of FTCS is a challenging task and requires a thorough understanding and effort at every step. Therefore it is necessary that a complete and in-depth analysis of the control system, faults affecting its desired performance and the most suitable control action be performed to design and develop an efficient and successful FTCS.

2.3 FTC of UAVs-A Historical Overview

There is no denying of the importance of UAVs in the current aerospace industry. Hence the FTC of UAVs has emerged as a popular and important research field since the past few years. Various papers and books have been published in the domain of FTC of UAVs. [72], [73] are good surveys on the FDI and FTC of UAVs. For the FDI of UAVs, several linear and non-linear techniques have been proposed and developed in the past. The different publications on FDI techniques for UAVs are depicted in Table 2-2:

Table 2-2: Publications on FDI methods for UAVs

FDI Method	Publication
Observer based	[74]-[81]
Kalman Filter	[82]-[89]
Unscented Kalman Filter	[90], [91]
Parity Space	[92]-[97]
Unknown Input Observers	[98]-[102]
H_∞ Filters	[103]-[106]
Parameter Estimation	[107]-[108]
Non-linear Geometry	[109]-[111]
Expert Systems	[112]-[113]
Neural Networks	[114]-[117]

Likewise, different papers have been published on the FTC methods for UAVs, a few of which are shown in the following Table:

Table 2-3: Publications on FTC methods for UAVs

FTC Method	Publication
Sliding Mode Controller	[118], [119]
Adaptive Control	[120], [121]
Control Allocation	[122]
Model Predictive Control	[123]
Linear Parameter Varying Control	[124]
MMST	[125], [126]

H_∞ Controllers	[127]

FTC of UAVs is presently an active area of study and exploration and many important and beneficial methodologies of FTC are underway.

CHAPTER 3: SYSTEM MODELLING WITH FAULTS

This chapter focuses on the development of the dynamic model of the FTC system. Faults are also incorporated in the system model. The noise disturbances and modelling uncertainties are also catered for in order to make the model work for practical situations and noisy environments.

3.1 System Modelling

Before moving to the development of the FTC technique suggested in this thesis, the system model is developed and explained. The state space model used in this thesis is linear time invariant (LTI). So linearization around a nominal point will have to be done if this FTC technique is to be applied on a non-linear model. The FTC technique developed in this research is applied on a Multi-Input Multi-Output (MIMO) state space model.

The LTI system model with the different components of the open-loop system shown in Figure 3.1. The plant dynamics are:

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

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

Where $x(t) \in \mathbb{R}^n$ is the state vector, $u(t) \in \mathbb{R}^q$ is the input signal vector and $y(t) \in \mathbb{R}^m$ is the output vector of the plant. $A_{n\times n}, B_{n\times q}, C_{m\times n}, D_{m\times q}$ are the time-invariant state-space matrices.

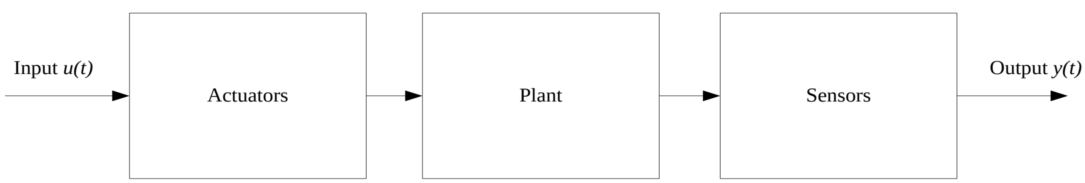

Figure 3.1: The open-loop model

In most of the practical situations, the LTI system model possesses some modeling uncertainties. The plant dynamics inclusive of these uncertainties are:

$$\dot{x}(t) = (A + \Delta A)x(t) + (B + \Delta B)u(t) \tag{3.3}$$

$$y(t) = (C + \Delta C)x(t) + (D + \Delta D)u(t) \tag{3.4}$$

Along with the modelling uncertainties, the LTI system experiences noise and unknown disturbances in the practical situations, so the plant dynamics are updated as follows:

$$\dot{x}(t) = (A + \Delta A)x(t) + (B + \Delta B)u(t) + E_1 n_1(t) \quad (3.5)$$

$$y(t) = (C + \Delta C)x(t) + (D + \Delta D)u(t) + E_2 n_2(t) \quad (3.6)$$

Where $n_1(t), n_2(t)$ are the noise vectors and E_1, E_2 are the noise/disturbance matrices of appropriate dimensions. If component faults are present in the system:

$$\dot{x}(t) = (A + \Delta A + \Delta A_c)x(t) + (B + \Delta B + \Delta B_c)u(t) + E_1 n_1(t) \quad (3.7)$$

$$y(t) = (C + \Delta C + \Delta C_c)x(t) + (D + \Delta D + \Delta D_c)u(t) + E_2 n_2(t) \quad (3.8)$$

Where $\Delta A_c, \Delta B_c, \Delta C_c, \Delta D_c$ represent the component fault matrices. On incorporating the actuator and sensor faults in the plant model we get:

$$\dot{x}(t) = (A + \Delta A + \Delta A_c)x(t) + (B + \Delta B + \Delta B_c)u(t) + E_1 n_1(t) + Bf_a(t) \quad (3.9)$$

$$y(t) = (C + \Delta C + \Delta C_c)x(t) + (D + \Delta D + \Delta D_c)u(t) + E_2 n_2(t) + f_s(t) \quad (3.10)$$

Where $f_a(t) \in R^q$ represents the actuator faults while $f_s(t) \in R^m$ is the sensors fault vector. The fault model is shown in Figure 3.2.

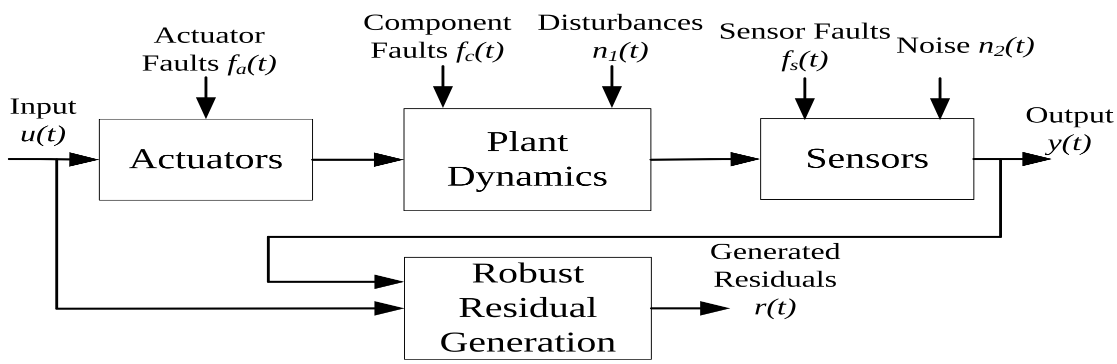

Figure 3.2: The system model with faults

The component faults and modelling uncertainties are included in the model as multiplicative faults which can make the task of applying FDI algorithms cumbersome. So we desire to model these as additive faults as follows:

$$\dot{x}(t) = Ax(t) + Bu(t) + E_1 n_1(t) + Bf_a(t) + F_1 f_c(t) \quad (3.11)$$

$$y(t) = Cx(t) + Du(t) + E_2 n_2(t) + f_s(t) + F_2 f_c(t) \quad (3.12)$$

Where $f_c(t)$ is the component faults vector which is inclusive of the modelling uncertainties. F_1, F_2 are the component fault matrices of appropriate dimensions.

As this thesis aims to develop an FTC technique for UAVs in the existence of actuator faults, only the actuator faults are considered in the model which is:

$$\dot{x}(t) = Ax(t) + Bu(t) + E_1 n_1(t) + Bf_a(t) \tag{3.13}$$

$$y(t) = Cx(t) + Du(t) \tag{3.14}$$

The fault model in (3.13)-(3.14) will be used for the design and formation of the suggested FTC method in this thesis.

CHAPTER 4: FAULT DETECTION AND ISOLATION

This chapter discusses the basic concepts, methods and techniques employed for FDI. A brief discussion of the concepts of redundancy, fault isolation and fault detectability is also provided.

4.1 FDI Basics

FDI is an important part of all Active FTCS. It provides all the necessary information about the faults; their time of detection and locations, to the reconfiguration module which then takes the most appropriate control action in the response [69]. FDI basically provides a binary decision in favour of or against the faults to the reconfiguration step. The FDI stage may or may not include detection, isolation and identification steps.

4.1.1 Redundancy

The base of the FDI is redundancy. The FDI stage utilizes the redundancy whether it is analytical or hardware, to decide for a fault. Hardware redundancy-as the name implies- exploits the concept of redundancy in either sensors or actuators, or both. Duplicative signals generated by different instruments such as sensors are compared and the resulting errors are then utilized for additional measurements. Some of the common methods used for hardware redundancy methods are residual generation method using parity generation based on sensor geometry or signal pattern, Cross channel monitoring (CCM) and signal processing methods for instance wavelet transformation etc. [37]. As the heart of hardware redundancy lies in employing extra equipments so it proves to be costly generally. This is the main reason for going for analytical redundancy methods.

Analytic redundancy methods use the mathematical model of the control system for FDI. Efficient algorithms and techniques are utilized for the analytical type of redundancy. As this method does not need any surplus hardware i.e. sensors and actuators, this approach is much more cost effective and decreases the total weight of the control system by removing the need of extra hardware and equipment. So this method is very useful for critical systems such as UAVs and other aerospace applications. However it is to be noted that this technique is much more complicated and challenging as it depends on algorithms which may not be very effective and robust in the occurrence of certain model uncertainties, noise, and unknown disturbances. Figure 4.1 summarizes the differences between the hardware and analytical redundancy methods.

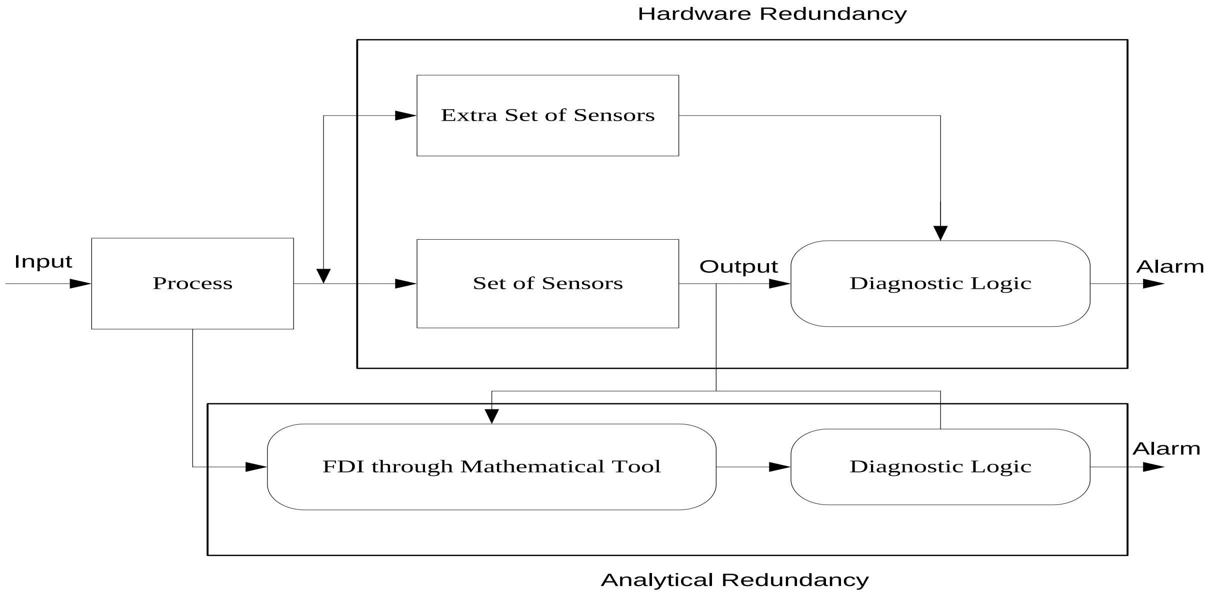

Figure 4.1: Different types of FDI redundancy [37]

Analytical Redundancy methods are either model based or non-model based. Table 4-1 illustrates some of the model and non-model based FDI techniques.

Table 4-1: FDI methods

Model Based FDI	**Non-Model Based FDI**
Full-State Observer Based	Neural Networks
Unknown Input Observers	Expert System
Kalman Filter Based	Genetic Algorithms
System Identification	Granular Computing
Parity Relations	Wavelet Transform
Optimization Based	Time Domain Analysis
Non-linear Systems	Frequency Domain Analysis

It is easier to design and implement model based FDI techniques as compared to the non-model based ones [30]. Model based FDI consists of two phases: Residual generation and Fault declaration. The robust model based FDI scheme designed in this research is demonstrated in Figure 4.2.

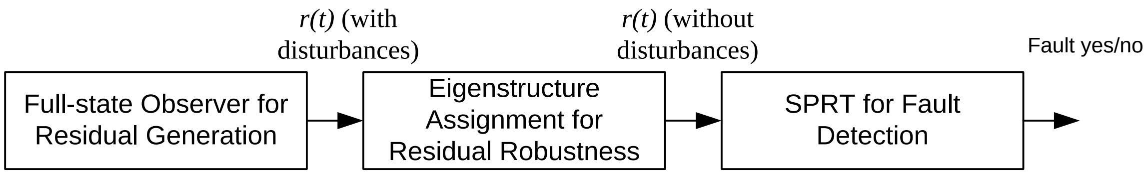

Figure 4.2: Robust FDI

4.1.2 Residual generation

The residual signal is in effect a function expressing the relationship between the input and output vectors of a plant, that is:

$$r(t) = f(u(t), y(t)) \tag{4.1}$$

In most of the cases, the residual signal is the difference between the actual output of the plant $y(t)$ and the output estimated by means of any of the analytical redundancy methods $\hat{y}(t)$:

$$r(t) = y(t) - \hat{y}(t) \tag{4.2}$$

In other words, a residual signal represents any inconsistency between the mathematical model and the actual system model [128]. Residual signals are not dependent on the control system's operating conditions and require information regarding the system's mathematical model only. This makes this method a very convenient one for model based FDI.

In order for fault detection, a residual evaluation function $J(r(t))$ is tested. The residual evaluation function is the mean of the residual signal in most of the cases.

$$J(r(t)) = E[r(t)] \tag{4.3}$$

The mean is tested:

$$\begin{cases} E[r(t)] = 0; & for \quad f(t) = 0 \\ E[r(t)] \neq 0; & for \quad f(t) \neq 0 \end{cases} \tag{4.4}$$

Since in most of the cases, residual generation takes place in the existence of noise and model uncertainties, the above test has to be modified for efficient fault detection so that the generated residuals become robust to these noise and disturbances. Table 4-1 enlists some of the various residual generation schemes for FDI. The model based technique utilizing full-state observers is employed in this thesis.

4.1.3 Fault detectability

The transfer function matrix between the residual signal and the fault(s) is called the "fault transfer matrix" and it is given as [128]:

$$G_{rf}(s) = H(s)G_f(s) = r(s)/f(s) \\ = \sum_{i=1}^{f}[G_{rf}(s)]_i f_i(s) \tag{4.5}$$

Where $[G_{rf}(s)]_i$ and $f_i(s)$ are the i th column of the fault transfer matrix and the i th row of the fault vector respectively. In order to detect the fault $f_i(s)$, the following condition must be fulfilled:

$$[G_{rf}(s)]_i \neq 0 \tag{4.6}$$

Or in other words, the fault(s) must be present and "detectable" in the residual signal and this is known as the "fault detectability condition." There also exists another fault detectability condition:

$$[G_{rf}(0)]_i \neq 0 \tag{4.7}$$

Known as the "strong fault detectability condition" of the residual.

4.1.4 Fault isolation

In an FDI system, different and multiple faults may be present. The fault isolation step isolates or separates the different types of faults. A vector of residuals is necessary for this purpose. Two approaches are used for fault isolation; the directional residual step and the structured residual step. [128] discusses both the approaches in detail. Since this thesis deals with only a single fault at a time hence fault isolation is not needed.

4.1.5 Fault decision

After the residual generation comes the decision making stage which decides whether or not a fault has arisen in the system. This is usually done by testing the residual signals against different thresholds. Efficient testing is done using different statistical tests for decision making. Some of the common statistical tests are:

1. Sequential Probability Ratio Test (SPRT)

2. Local Approach
3. Generalized Likelihood Ratio (GLR) Test
4. Cumulative Sum (CUMSUM) Test

An explanation of the above tests may be obtained from [37]. The SPRT is used in this research for fault decision making [37].

CHAPTER 5: FULL-STATE OBSERVER BASED RESIDUAL GENERATION

The method used for the residual generation for FDI in this research is the full-state observer based method which is discoursed in detail in this chapter.

5.1 Full-state Observers-An Overview

The full-state observer approach employs the theory of the simple Luenberger observer for generating the residual signals for FDI. The basic notion is to reconstruct or estimate the outputs or states of a control system using the measurements obtained by the sensors. The general structure of the Luenberger observer is presented in Figure 5.1.

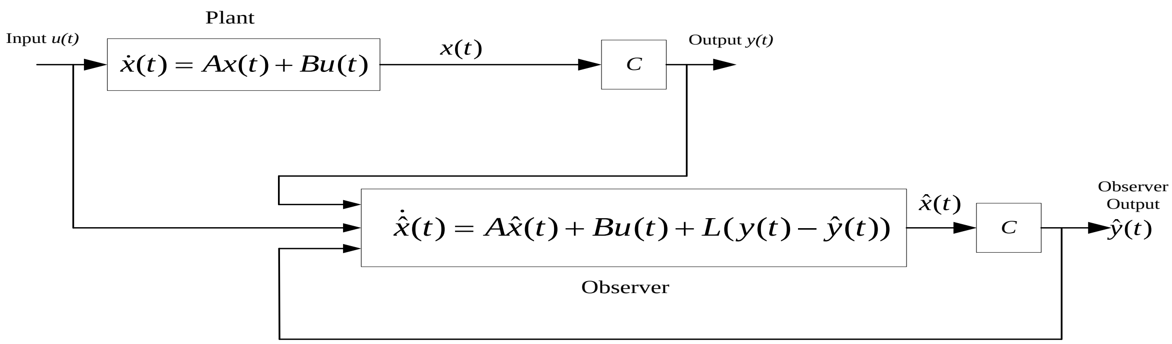

Figure 5.1: Luenberger Observer

The state space model of the observer is:

$$\dot{\hat{x}}(t) = A\hat{x}(t) + Bu(t) + L(y(t) - \hat{y}(t)) \tag{5.1}$$

$$\hat{y}(t) = C\hat{x}(t) \tag{5.2}$$

Here $\hat{x}(t)$ represents the estimated state vector and L is the observer gain matrix. The error between the states and their estimates is given as:

$$\tilde{x}(t) = x(t) - \hat{x}(t) \tag{5.3}$$

The error dynamics become:

$$\begin{aligned} \dot{\tilde{x}}(t) &= \dot{x}(t) - \dot{\hat{x}}(t) \\ &= Ax(t) + Bu(t) - A\hat{x}(t) - Bu(t) - L(y(t) - C\hat{x}(t)) \\ &= (A - LC)\tilde{x}(t) \end{aligned} \tag{5.4}$$

In order for the error to go to zero asymptotically $(A - LC)$ should be a stable matrix, that is, all the eigen values of this matrix should be in the left half plane LHP. So L should be calculated keeping this criterion in mind.

5.2 Residual Generation through Observers

The design of the Luenberger observers for FDI has been discussed by Clarke and Patton and Kangethe in [129] and [130] respectively. The basic idea is the same as in the circumstance of a Luenberger observer. Using the fault model developed in (3.13)-(3.14) and the observer dynamics from (5.1)-(5.2), we calculate the residual signal as the weighted difference between measured and estimated outputs:

$$r(t) := W(y(t) - \hat{y}(t)) = WC\xi(t) \tag{5.5}$$

Where $W \in R^{p \times m}$ is the residual weighting matrix and $\xi(t)$ is the state estimation error of the system model with faults. Therefore:

$$\xi(t) = x(t) - \hat{x}(t) \tag{5.6}$$

And the error dynamics are:

$$\dot{\xi}(t) = (A - LC)\xi(t) + Bf_a(t) + E_1 n_1(t) \tag{5.7}$$

The Laplace transform of the residual signal from (5.5) is:

$$R(s) = WC\Xi(s) \tag{5.8}$$

The Laplace transform of the error dynamics from (5.7) is:

$$\begin{aligned} s\Xi(s) &= (A - LC)\Xi(s) + BF_a(s) + E_1 N_1(s) \\ \therefore \Xi(s) &= (sI - A + LC)^{-1}[BF_a(s) + E_1 N_1(s)] \end{aligned} \tag{5.9}$$

Putting value of $\Xi(s)$ from (5.9) to (5.8):

$$R(s) = WC(sI - A + LC)^{-1}[BF_a(s) + E_1 N_1(s)] \tag{5.10}$$

It can be witnessed that the residual signal is non-zero even when the faults are not present. Therefore while calculating the residual signals, the weighting matrix W should be calculated such that robustness is attained; the residuals become decoupled from noise and disturbances. This is achieved through a method known as “left eigenstructure assignment” and is discussed in the following chapter.

CHAPTER 6: EIGENSTRUCTURE ASSIGNMENT

This chapter discusses the method used for achieving the disturbance decoupling in residual generation- the eigenstructure assignment method. A background of this method along with its application for robust FDI is also explained.

6.1 Eigenstructure Assignment-Basics

Generating robust residuals is making the residuals independent or insensitive to the noise disturbances or model uncertainties. Different approaches and tools have been developed for producing residual robustness such as Unknown Input Observers (UIO) and Eigenstructure assignment method. UIOs also generate robust residuals decoupled from noise disturbances and uncertainties by first making the state estimation errors free of disturbances (unknown inputs- hence the name) and then linearly transforming the errors into weighted output estimation errors [128]. As described, UIOs require calculation of state estimation errors first which are mostly not needed for FDI, so this calculation becomes surplus. Eigenstructure assignment in contrast is a direct approach for achieving disturbance decoupling in residuals which does not require state estimation errors to be decoupled first. So this approach is followed in this thesis also.

Eigenstructure assignment for FDI is basically a method in which the eigenstructure i.e. eigen values and left or right eigenvectors-of the full-state observers is computed in such a manner that the eigenvectors becomes orthogonal or parallel and ultimately robust to the noise and disturbance direction vectors. Eigenstructure assignment is of two types; left and right eigenstructure assignment depending on which type of the eigenvectors is computed first. The method of left eigenstructure assignment by introduced by Patton et al. and is discussed and further elaborated in [130]. Since the left eigenstructure assignment for residual robustness is a well-developed technique, it is therefore employed in this research.

In order to fully develop and understand the method of left eigenstructure assignment, the following terms and their definitions must first be understood and clarified.

6.1.1 Rank of a matrix

The maximum number of linearly independent row (or column) vectors of a matrix **A** is termed as the rank of matrix **A.** For example:

$$\mathbf{A} = \begin{bmatrix} 1 & 0 & 2 \\ 2 & 0 & 4 \\ 3 & 1 & 9 \end{bmatrix}$$

Has rank=2 because the first two rows are linearly dependent.

6.1.2 Vector space

The nonempty set *S* of vectors such that all the linear combinations of any two vectors **a** and **b** in *S* i.e. $\alpha\mathbf{a}+\beta\mathbf{b}$, where α and β are any real numbers, are elements of the set *S*. The vector elements of *S* satisfy the laws of addition and scalar multiplication.

6.1.3 Vector subspace

The subspace of *S* is a nonempty subset of *S*, including *S* itself, that forms a vector space as regards the laws of addition and scalar multiplication defined for the vector elements of the set *S*.

6.1.4 Dimension of vector space

The maximum number of linearly independent vectors in the set *S* is termed as the dimension of *S* or dim *S*. The dimension is equivalent to the rank of a matrix **A**.

6.1.5 Basis of vector space

The set consisting of the maximum possible number of linearly independent vectors in the set *S* is the basis for *S*. Hence the number of vector (elements) of a basis of *S*= dim *S*.

6.1.6 Span of vectors

The set consisting of all the maximum possible linear combinations of a given set of vectors *V* is called the span of the given set of vectors in *V*. The span forms a vector space as well.

6.1.7 Null space

The solution set of the homogenous system $\mathbf{Ax}=\mathbf{0}$ is the null space of **A**, which is also a vector space *N*. The dimension dim *N* is called the nullity.

6.1.8 Eigenvalue

Eigenvalues are related to a linear system of equations and are also known as the characteristic roots, proper values or latent roots of a linear system [132]. If **A** is a square matrix of order *n*, then for some scalar λ :

$$\mathbf{Ax} = \lambda\mathbf{x} \tag{6.1}$$

Where $\mathbf{x} \in \mathbb{R}^n \neq \mathbf{0}$, then $\lambda \in \mathbb{C}^n$ is termed as the eigenvalue of **A.**

6.1.9 Eigenvector

The vector **x** in (6.1) is the corresponding (right) eigenvector of **A.** It is a column vector. Eigenvectors may be left or right eigenvectors. If we have:

$$\mathbf{x_L A} = \lambda\mathbf{x_L} \tag{6.2}$$

Then the row vector $\mathbf{x_L}$ is called the left eigenvector of **A.** In most of the cases, the right eigenvectors are sufficient. The eigenvectors corresponding to one eigenvalue λ of **A** form a vector space known as the "eigenspace" of **A** for λ .

6.1.10 Eigenstructure

The following equation represents the complete eigenstructure of **A:**

$$\mathbf{AV} = \mathbf{VL} \tag{6.3}$$

Where $\mathbf{V}$ is a diagonal matrix with the eigenvalues as the main or principal diagonal entries.

6.2 Left Eigenstructure Assignment

The manifestation of noise and model uncertainties in the control system might make it challenging to separate and detect the faults occurring in the system. This might sometimes result in false and missed alarms during FDI. The left eigenstructure assignment method caters for these challenges efficiently.

The transfer function matrix between the residuals and actuator faults from (5.10) is:

$$G_{r,f}(s) = R(s)/F_a(s) = WC(sI - A + LC)^{-1}B \tag{6.4}$$

And between the residuals and disturbance matrix is:

$$G_{r,n}(s) = R(s)/N_1(s) = WC(sI - A + LC)^{-1}E_1 \tag{6.5}$$

In order to achieve residual robustness, it is desired to null the transfer function matrix formed between residuals and disturbances, that is:

$$G_{r,n}(s) = WC(sI - A + LC)^{-1}E_1 = 0 \tag{6.6}$$

So once the values W and L are calculated in such a way that (6.6) is satisfied, the residual robustness can be attained. It is to be noted that the number of rows p of W should be selected so that $p \leq m$ in order to avoid any linearly dependent rows in W . Normally:

$$p = m - rank(CE_1) \leq m \qquad (6.7)$$

is chosen as the row number for W .

Theorem 6.1:

The necessary and sufficient conditions for satisfying (6.3) are

1. $WCE_1 = 0$ and
2. All rows of matrix $H = WC$ are the left eigenvectors of $(A - LC)$ corresponding to the chosen real and distinct eigenvalues.

Hence the above theorem should be fulfilled so that the disturbance decoupling is obtained. The mathematical proof of Theorem 6.1 may be obtained from [128].

To summarize, the following steps are taken to generate disturbance decoupled residuals through the left eigenstructure assignment method:

1. The residual weighting matrix W is calculated first so that the condition $WCE_1 = 0$ is satisfied.
2. The desired set of eigenvalues is chosen next for the observer. All the rows of WC are then equated to the p left eigenvectors of the observer $(A - LC)$ and calculate the values of these eigenvectors. The remaining $(n - p)$ eigenvectors are chosen so that good conditioning is ensured.
3. Finally compute the observer gain using an appropriate eigenstructure assignment technique as in [130].

The above steps can be further illuminated by means of the following example given in [131]:

Example 6.1:

Consider the following system matrices:

$$A = \begin{bmatrix} 0 & 3 & 4 \\ 1 & 2 & 3 \\ 0 & 2 & 5 \end{bmatrix}; n = 3$$

$$B = \begin{bmatrix} 0 \\ 1 \\ 2 \end{bmatrix}$$

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

$$D = 0$$

$$E_1 = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$$

1. By satisfying $WCE_1 = 0$; we get:

   $$W = \begin{bmatrix} 0 & 1 \end{bmatrix}; p = 1$$

   So that $WC = [\ 0 \quad 0 \quad 1]$ which is taken as an eigenvector l_1 of $(A - LC)$.

2. The desired set of eigenvalues is chosen as $\lambda = \begin{bmatrix} -1 & -2 & -3 \end{bmatrix}$. l_1 is the corresponding eigenvector of $\lambda = -1$. Now the remaining $(n - p) = (3 - 1) = 2$ eigenvectors l_1, l_2 which lie in the subspace spans $(\lambda_1 I - A^T)^{-1} C^T, (\lambda_2 I - A^T)^{-1} C^T$ have to be calculated.

3. The observer gain is calculated using the method provided in Appendix A:

   $$L = \begin{bmatrix} 9 & 4 \\ 7 & 3 \\ 2 & 6 \end{bmatrix}$$

It can be observed that both the decoupling conditions are satisfied that is, $WCE_1 = 0$ and the transfer function matrix $G_{r,n}(s) = WC(sI - A + LC)^{-1} E_1 = 0$, so the generated residuals are robust.

CHAPTER 7: SEQUENTIAL PROBABILITY RATIO TEST

After the generation of robust residuals, the next phase is the decision making phase for faults. This chapter discusses and explains the statistical testing of residuals for detection of faults. A discussion of the Sequential Probability Ratio Test used in this research for the testing of residuals is provided in this chapter along with the preliminaries.

7.1 An Overview of Hypothesis Testing

The concept of hypothesis testing forms a vital part in statistics and statistical inference. Hypothesis testing basically allows the user whether to accept or reject a statement or an assumption called hypothesis regarding a parameter of the population at hand. This decision is made on the basis of information obtained from sampled data of the population. The acceptance of the hypothesis is equivalent to considering it true while rejection means the hypothesis is considered as false. When the sampled data supports the hypothesis, the hypothesis is accepted whereas the hypothesis is rejected when the sampled data cannot support the hypothesis.

7.1.1 Null and alternate hypotheses

Null hypothesis, denoted by H_0, is the default hypothesis or statement which is put up for testing for possible rejection or nullification. The null hypothesis generally refers to the common view and is assumed to be true unless rejected or dismissed through testing. The null hypothesis forms an essential part of any statistical testing and should always be precise and unambiguous. H_0 may or may not have a numerical value assigned to it. In the simplest terms, null hypothesis is the opposite of the alternative hypothesis explained below.

Alternative hypothesis H_1 as the name implies is the substitute or the other hypothesis accepted when the null hypothesis gets rejected on the basis of some evidence. It usually refers to the observations obtained as a result of some real effect or experiment.

7.1.2 Formulation of hypotheses

The formation of precise and appropriate hypotheses is essential for good statistical testing, but it is not always a trivial task. Care must be taken while formulating the null and alternate hypotheses and they should be formed in such a manner that they are opposites of each other, that is, when one hypothesis is true, the other must be false and vice versa. The rule of thumb is to make H_1 the statement the experimenter wants to regard as true. In other words, the claim an experimenter wants to make with substantial evidence should be formed as the alternative hypothesis. The rejection of the claim is regarded as the null hypothesis accordingly.

The hypothesis testing is done on a parameter θ of the target population. For instance, if θ_0 is the specified value of the parameter θ, then the hypothesis may be formed as follows:

$$H_0 : \theta = \theta_0 \tag{7.1}$$

$$H_1 : \theta \neq \theta_0 \tag{7.2}$$

7.1.3 Error (misidentification) probabilities

It is quite possible that the hypothesis formulation and testing may lead to wrong decisions and errors. In other words, a null or alternate hypothesis may be rejected when it is in reality true, which is called the "Type I error" or a "False Alarm." It is also quite possible that a hypothesis may be accepted when actually it is false. This is known as the "Type II error" or a "Missed Alarm." These two types of errors are illustrated in the following Table:

Table 7-1: Types of errors in hypotheses testing

True/ False	**Decision**	
	H_0 Accepted	**H_0 Rejected (or H_1 Accepted)**
H_0 is True	No Error	Type I Error
H_0 is False	Type II Error	No Error

The probability of the Type I error is represented by α which is the probability of rejecting H_0 (or accepting H_1) when it is true and is called the "False Alarm Probability." Similarly, the probability of the Type II error is symbolized by β and it is the probability of accepting H_0 (or rejecting H_1) when it is false (i.e. H_1 is true) and is known as the "Missed Alarm Probability." To summarize:

$$\alpha = P(\text{Type I error}) = P(\text{reject } H_0 / H_0 \text{ is true})$$

$$\beta = P(\text{Type II error}) = P(\text{accept } H_0 / H_0 \text{ is false})$$

7.1.4 Probability density function (pdf)

The probability density function (pdf) represents the "density" of probability of the random variable X at a specific point x [134] and is given as:

$$f_X(x) = \frac{dF_X(x)}{dx} \tag{7.3}$$

Where $F_X(x)$ is the cumulative distribution function (cdf), which is the probability of the event: $\{X \le x\}$. There are different types of pdfs depending upon the various types of random variables involved.

7.1.5 Gaussian distribution

The Gaussian or Normal probability distribution is the most frequently occurring distribution in most problems involving random variables-hence the name "normal probability distribution." The probability density function (pdf) of the normal distribution is:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-[(x-\mu)^2/2\sigma^2]} \tag{7.4}$$

Where $-\infty < x < \infty, \sigma > 0$, $\mu \in \mathbb{R}$ is the mean and $\sigma \in \mathbb{R}$ is the standard deviation of the normal distribution. The normal distribution can therefore be categorized completely by its parameters μ and σ, and is often denoted as $N(\mu, \sigma^2)$. The normal distribution has a symmetric bell-shaped curve known as the "normal curve".

7.1.6 Conditional probability density function

For a given event A, the conditional pdf of a random variable X is:

$$\begin{aligned} f(x|A) &= P(X = x|Y = A) \\ &= \frac{P(X = x \cap Y = A)}{P(Y = A)} \end{aligned} \tag{7.5}$$

Note the conditional pdf is also a non-negative function.

7.1.7 Likelihood ratio test

In statistics, a likelihood ratio test describes how much more "likely" a given data fits one of the two test hypotheses. This test is centred on the likelihood ratio which is stated as follows:

$$\Lambda(x) = \frac{L(\theta_0 | x)}{L(\theta_1 | x)} \tag{7.6}$$

Where $L(\theta|x) = f_\theta(x)$ is the likelihood function of the parameter θ when the outcome of X is given as x. The likelihood ratio test is then given for a “critical value” c where $0 \le c \le 1$ (7.1), (7.2):

- If $\Lambda > c$; H_0 is accepted
- If $\Lambda < c$; H_0 is rejected

For some applications, the natural logarithm of the likelihood ratio is taken called the “log-likelihood ratio” and it is more convenient to use and apply.

7.2 SPRT

The Sequential Probability Ratio Test was introduced by Abraham Wald in 1947 [133] as a modification to Neymar and Pearson’s 1933 lemma. This test was originally proposed to check and maintain quality in the production market. The items are tested in a sequential manner and the results are reviewed after each test. The SPRT is widely used in maintaining quality control.

In this thesis, the SPRT is used to detect changes in the residual signals and declare faults. In SPRT, statistical hypothesis testing is basically done on the chosen parameter θ of the system as stated in equations (7.1) and (7.2). Here H_0 represents the no fault or fault free conditions for the system while H_1 is formulated for the case where a fault has arisen in the system. SPRT is essentially a binary hypothesis test [135] for declaring a fault or no fault in the residual signals. Given that no fault is declared in the system, H_0 is considered true and the sampling and SPRT continues. As soon as the decision is taken in favour of the alternative hypothesis H_1, a fault is said to have occurred in the system and SPRT is terminated. Studies show that the SPRT provides the lowest error probabilities and shortest detection time for Gaussian distributes signals. SPRT is especially useful for noisy analogue signals and slowly forming or incipient faults and is quite easy to implement. Since the residuals generated are normally distributed, SPRT is used for the efficient testing and fault detection in this thesis.

Let $x_0, x_1, x_2, x_3 ..., x_n$ represent a sequence of observations obtained from a sample population which are put to the SPRT. The log-likelihood ratio of this sequence is [37]:

$$\Lambda_n = \log \frac{p_{\theta_1}(x_n \left| x_{n-1,......,} x_0 \right.)}{p_{\theta_0}(x_n \left| x_{n-1,......,} x_0 \right.)} \tag{7.7}$$

Where $p_{\theta}(x_n \left| x_{n-1,......,} x_0 \right.)$ is the conditional pdf of the observation x_n with respect to the parameter θ.

Next the cumulative sum of the log-likelihood ratio is computed recursively:

$$S_n = S_{n-1} + \Lambda_n \tag{7.8}$$

The testing process is continued until one of the following conditions get fulfilled:

- If $S_n \geq B$, H_1 is accepted and a fault is declared
- If $S_n \leq A$, H_0 is accepted and no fault is declared
- Else the test is continued.

Where A, B are user-defined design parameters depending upon the chosen error probabilities. The flow chart for a generalized SPRT is illustrated in Figure 7.1.

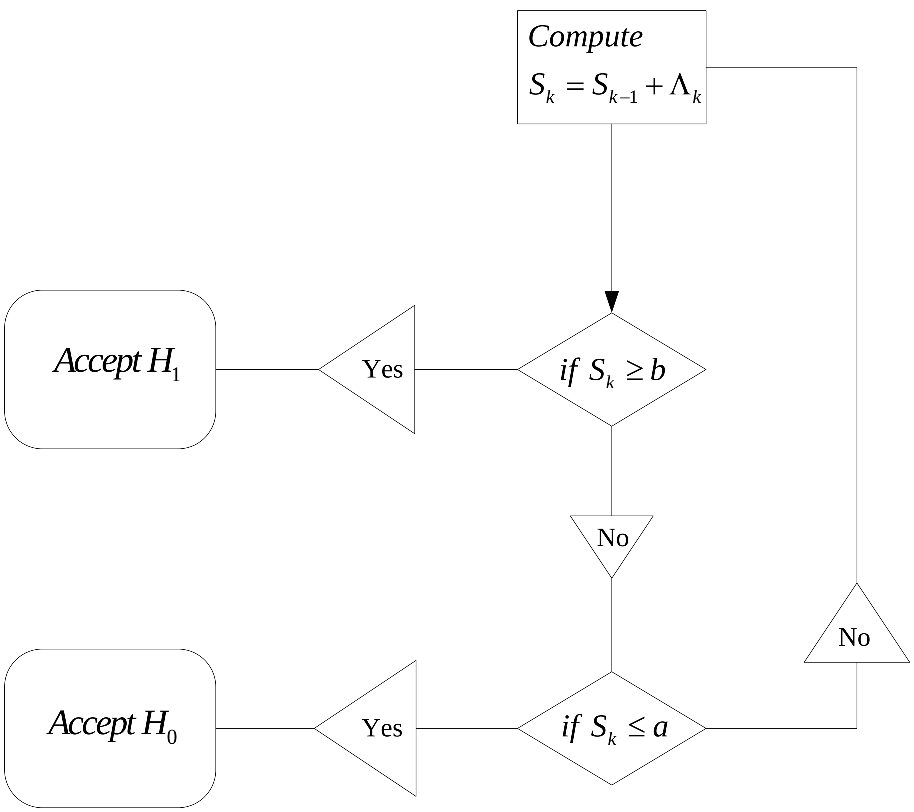

Figure 7.1: SPRT Flow Chart

7.2.1 SPRT for residuals possessing Gaussian distribution

It is observed that the robust residuals generated by the full-state observer are normally distributed. So the SPRT for normally distributed signals is developed and employed. Let $\{R_n\} = r_0, r_1, r_2, r_3, ..., r_n$ be the sequence or random process of normally distributed residual signals generated and r_k be a sample of the process R_n at the time instant t_k. Under normal conditions, the samples r_k should have a Gaussian pdf with mean=*0* and variance=σ^2. If the system's performance malfunctions or degrades, the mean of the sequence of samples r_k does not remain zero and drifts to a new value so that the sequence possesses a new Gaussian pdf with mean= $+M$ and variance=σ^2, where M is pre-defined by the user. This is called the "Positive Mean SPRT" and is employed in this thesis. The test hypotheses for the positive mean SPRT are formulated as follows:

$$H_0 : r_k \text{ has Gaussian pdf with mean } \mu = 0 \text{ and variance} = \sigma^2 \tag{7.9}$$

$$H_1 : r_k \text{ has Gaussian pdf with mean } \mu = +M \text{ and variance} = \sigma^2 \tag{7.10}$$

And the error probabilities are:

$$\alpha = \text{False Alarm Probability} \tag{7.11}$$

$$\beta = \text{Missed Alarm Probability} \tag{7.12}$$

For formulating SPRT test index, we must first define the likelihood ratio l_n :

$$l_n = \frac{\text{probability of } \{R_n\} \text{ given } H_1 \text{ is true}}{\text{probability of } \{R_n\} \text{ given } H_0 \text{ is true}} \tag{7.13}$$

After *nth* sample of the sequence, the SPRT is taken as the product of the probability ratio (PR) obtained at each step *k*:

$$\begin{aligned} l_n &= (PR)_1 \bullet (PR)_2 \bullet (PR)_3 \bullet .... \bullet (PR)_n \\ &= \sum_{k=1}^{n} \frac{f(r_k | H_1)}{f(r_k | H_0)} \end{aligned} \tag{7.14}$$

Where $f(r_k | H)$ is the conditional pdf of the random process *R*. Since *R* is normally distributed, the likelihood that H_1 is true is given as:

$$L(r_1, r_2, r_3, ..., r_n | H_1) = \frac{1}{\sigma^n (2\pi)^{n/2}} \exp\left[\frac{-1}{2\sigma^2} (\sum_{k=1}^{n} r_k{}^2 - 2\sum_{k=1}^{n} r_k M + \sum_{k=1}^{n} M^2) \right] \tag{7.15}$$

And the likelihood that H_0 is true is given as:

$$L(r_1, r_2, r_3, ..., r_n | H_0) = \frac{1}{\sigma^n (2\pi)^{n/2}} \exp\left[\frac{-1}{2\sigma^2} (\sum_{k=1}^{n} r_k{}^2) \right] \tag{7.16}$$

Dividing (7.15) by (7.16) to get the likelihood ratio l_n :

$$l_n = \exp\left[\frac{-1}{2\sigma^2} \sum_{k=1}^{n} M(M - 2r_k) \right] \tag{7.17}$$

Next the acceptance thresholds are defined as follows:

$$A = \frac{\beta}{(1-\alpha)} \tag{7.18}$$

$$B = \frac{(1-\beta)}{\alpha} \tag{7.19}$$

Where A is the lower threshold and B is the upper threshold. Note that both the thresholds are related to the error probabilities. According to Wald, at each time index t_k , the likelihood ratio is compared to the thresholds and a decision is taken in favour of or against the fault as follows:

- If $l_n \geq A$, the test is stopped and the null hypothesis H_0 is accepted, i.e. no fault has occurred
- If $l_n \leq B$, the test is stopped and the null hypothesis H_1 is accepted i.e. a fault has occurred
- If $A < l_n < B$, neither hypothesis is accepted and the test continues.

For SPRT, the positive mean test index is calculated by taking the natural logarithm of the likelihood ratio l_n in (7.17) as follows:

$$\ln(l)_n = \ln(\exp\left[\frac{-1}{2\sigma^2} \sum_{k=1}^{n} M(M - 2r_k) \right])$$

$$\therefore \text{SPRT} = \frac{-1}{2\sigma^2} \sum_{k=1}^{n} M(M - 2r_k) \tag{7.20}$$

$$\text{or}\, \text{SPRT} = \frac{M}{\sigma^2} \sum_{k=1}^{n} (r_k - \frac{M}{2})$$

Similarly taking the natural logarithm of the acceptance thresholds for SPRT:

$$\ln(A) = \ln\left(\frac{\beta}{1-\alpha} \right) \tag{7.21}$$

$$\ln(B) = \ln\left(\frac{1-\beta}{\alpha}\right) \tag{7.22}$$

At the initial step of SPRT, the test index in (7.20) is set to zero and the system disturbance magnitude for M and the error probabilities α and β are defined. The system disturbance magnitude means the number of standard deviations the pdf must shift in the positive direction to generate an alarm. Then at each time period, the SPRT index is compared to the upper and lower thresholds given in (7.21) and (7.22) respectively to produce one of the following outcome:

- If $\text{SPRT} \le \ln(A) \le \ln\left(\frac{\beta}{1-\alpha}\right)$; H_0 is accepted
- If $\text{SPRT} \ge \ln(B) \ge \ln\left(\frac{1-\beta}{\alpha}\right)$; H_1 is accepted
- Otherwise if $\ln\left(\frac{\beta}{1-\alpha}\right) < \text{SPRT} < \ln\left(\frac{1-\beta}{\alpha}\right)$; no conclusion, testing continues.

Utilizing the SPRT in the thesis, efficient and optimal fault decision results are obtained. SPRT is the last stage of FDI as shown in Figure 4.2.

CHAPTER 8: MULTIPLE MODELS SWITCHING AND TUNING METHOD AND LINEAR QUADRATIC GAUSSIAN REGULATORS

After FDI stage, the active FTC requires a reconfiguration step to maintain overall stability and produce desired and appropriate control actions. This chapter provides an overview of the reconfiguration step in FTC and an in depth discussion on the method used for reconfiguration in this thesis.

8.1 Reconfiguration

The Passive FTC is an off-line method for FTC and is based on the theory and concepts of robust control. It therefore does not need any FDI module. Active FTC on the other hand is based on information on faults provided by the FDI stage and is more efficient and interactive. This research uses the Active FTC ideas for reconfiguration and maintaining stability.

As shown earlier in Figure 2.2, Active FTC is in turn classified into projection type FTC and online adaptation methods. Projection type is designed in this thesis for reconfiguration and requires a priori information regarding the type of faults for designing the possible appropriate controllers. Projection type is sub-divided into three groups; prediction, model switching/ blending and scheduling. Due to its efficiency and better transient performance, the projection type FTC is preferred over online adaptation methods [137].

8.2 Terminology

In this section, the general terms essential for the theory of Multiple Models Switching and Tuning (MMST) are briefly discussed [138]:

8.2.1 Model

The representation of the essential parts of the system in a convenient and suitable form is called a model of the system. Different forms of models may be developed for a system depending upon the purpose and convenience. The most common and suitable method of demonstrating the behaviour of a system is by formation of a mathematical model of the system. In the MMST technique, multiple models (both heuristic and mathematical) formed through different analysis and assumptions are used to achieve improved and efficient performance.

8.2.2 Environment

The mathematical model of the system includes both the plant dynamics and external environment parameters. In most cases the plant dynamics are represented by differential equations as follows:

$$\dot{x}(t) = f(x(t), u(t), p) \tag{8.1}$$

$$y(t) = h(x(t), p) \tag{8.2}$$

Where the parameter vector p might represent different environments including different faults, disturbances and model uncertainties.

8.2.3 Multiple models

Practically a plant operates in different environments so any change in the environment parameters may bring about a variation in the input-output characteristics of the system and these changes may be rapid or sometimes even discontinuous. A single model if used for representing the plant and its dynamics will have to be adapted each time the environment changes. This may lead to a slow response and a large transient error. Therefore multiple models are necessary to control different environments rapidly. If models of the plant pertaining to different environments are available in advance, the corresponding controllers can also be designed *a priori*. During system operation, the task remains only to identify the current environment and model to determine the correct controller efficiently. Thus multiple models may be preferable to a single model in most of the cases.

8.2.4 Switching

In rapidly or sporadically switching environments, the reconfigurable control strategy must be fast enough to detect these rapid changes in the parameters of the environment and to switch accordingly to avoid permanent and detrimental failures. By using fixed multiple models, the appropriate pre-designed controller can be selected swiftly from a set of available controllers. This type of reconfigurable control though not changing (adapting) incrementally, can also be considered to be adaptive and is efficient in rapidly varying practical environments.

8.2.5 Tuning

Incremental and gradual estimation and adjustment of control parameters is known as tuning in the classical adaptive control theory [139].

8.2.6 Switching and tuning

In a general MMST scheme, the identification of the environment generally occurs in two steps; switching and tuning. The rapid selection of the model with the least error, as per a specific performance principle, is switching and then the adjustment of its parameters gradually to improve accuracy is tuning. Switching is basically determines when the current model of the plant is unsatisfactory, that is when to switch, and which one to replace it with, that is what to switch to. Tuning is involved in determining the rule by which the parameter value of the controller is to be adjusted at each time step [140]. Therefore it can be stated that switching is rapid but generally not adequately accurate whereas tuning is comparatively slower but improves the performance of the system [139].

8.3 Multiple Models Switching and Tuning (MMST)

There has been an abundant research and development in the domain of adaptive control by means of multiple models switching and tuning during the past decade. This control method was invented in the early 1990's and proved to be greatly beneficial for the control of plants in rapidly changing environments [139]. The MMST is shown to work best with varying flight conditions therefore it is used in this thesis for reconfiguration [69].

8.3.1 General architecture of the multiple models control system

The general design of the multiple models control system which estimates the current environment and its parameters is shown in Figure 8.1. The plant P that is to be reconfigured and controlled has the input $u(t)$ and the output is $y(t)$. The desired output of the system is $y_d(t)$ and the control error is given as $e_c(t) = y_d(t) - y(t)$ which is to be asymptotically driven to zero through reconfiguration. There are N identification models denoted by $\{M_i\}_{i=1}^{N}$ which have the corresponding outputs $\{y_i\}_{i=1}^{N}$ and are operating in parallel. Each M_i has a corresponding controller C_i with output $u_i(t)$ which is designed so that it achieves the control objectives of the system. At each time step, the identification errors $e_i(t) = \hat{y}_i(t) - y(t)$ are computed for each of the models and a switching rule decides which model and the corresponding control should be switched on to provide the input to the plant. It should be added that the controller must be designed keeping in mind the intended performance, stability and efficiency requirements. The aforementioned MMST architecture is quite broad-spectrum and applies to both linear and nonlinear systems.

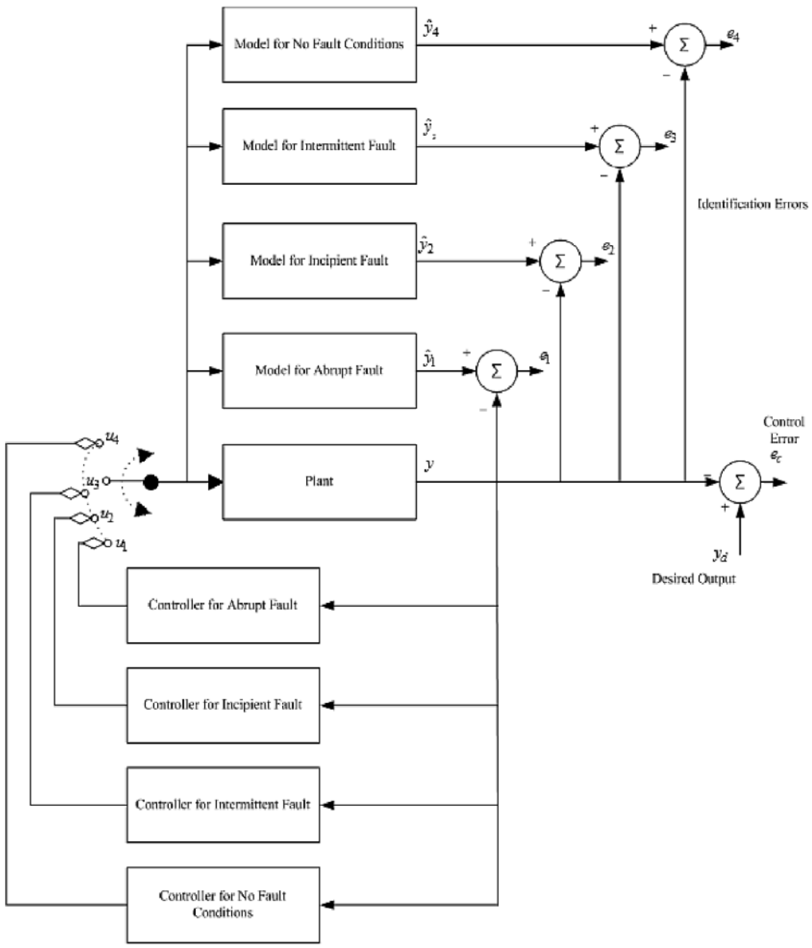

Figure 8.1: General MMST architecture

8.3.2 The switching criterion for MMST

The formation and the choice of a switching criterion forms an important part of the MMST method. The switching criterion relies upon the *a priori* information available about the plant and affects the stability and performance of the reconfiguration step. When choosing any switching criterion, the following important issues need to be addressed [139]:

1. When should the switching from one to another model take place?
2. Which model should be switched on?
3. Is the switching scheme stable?
4. Will the switching continue or will it stop after some finite amount of time?
5. Is the performance improved by using the switching scheme?

The aforementioned issues should be appropriately addressed when designing the MMST architecture. Different switching criterion can be formed which tackle the above issues satisfactorily. The switching criterion is in fact the performance index established on the basis of the identification errors $e_i(t)$ which may be designed in one of the following forms:

1. $J_i(t) = e_i^2(t)$
2. $J_i(t) = \int_0^t e_i^2(\tau)d\tau$
3. $J_i(t) = \alpha e_i^2(t) + \beta \int_0^t e_i^2(\tau)d\tau$
4. $J_i(t) = \alpha e_i^2(t) + \beta \int_0^t e^{-\lambda(t-\tau)} e_i^2(\tau)d\tau$

At each time instant *i*, the most appropriate performance index $J_i(t)$ for each model is calculated and the controller corresponding to the least value of $J_i(t)$ that is $\min_i\{J_i(t)\}$ is employed to provide the control input to the plant at the instant *i* as this minimizes the regulation or the tracking errors during reconfiguration.

While making a choice among one of the above stated performance indices, both instantaneous and long-term accuracy measures need to be kept in mind to ensure reliable performance. The analysis regarding this choice is done by empirical studies and observations. Studies in [141] show that if the performance index no.1 is chosen, then the transients in $e_i^2(t)$ are quickly detected but the switching gets tremendously rapid and results in poor control. Choosing the performance index no.2 may lead to good information about the steady-state errors but it may result in a slow response to the transient peaks. If the performance index no.3 is selected, one has to wait for a time period of $\min_i\{J_i(t)\}$ before switching on the controller to prevent randomly rapid switching [141]. Motivated by the quadratic optimal control theory, the fourth performance index i.e. $J_i(t) = \alpha e_i^2(t) + \beta \int_0^t e^{-\lambda(t-\tau)} e_i^2(\tau)d\tau$ is chosen as a switching criterion [141]. Where $\alpha \geq 0, \beta > 0, \lambda > 0$ are design parameters depending on the user's choice. A suitable trade-off is obtained between instantaneous and long-term accuracy measures by determining appropriate values for α, β. The long-term memory of the performance index is determined through λ which also ensures the boundedness of the index $J_i(t)$ for the cases where $e_i(t)$ is bounded [140]. All the parameters may be chosen through experience and observations off-line.

It is to be noted that at a given time instant, only one controller is active to provide the control and hence the performance evaluation of any contender controller can be done only after its activation. On the other hand, using the above mentioned MMST architecture, at every instant the performance of each of the identification models can be assessed in parallel and this leads to better and appropriate results. Hence during calculating the performance indices, the performance of the models instead of the controllers should be used as a yard stick. In other words, identification errors should be used rather than the control errors.

8.3.3 Choice of models

Given past knowledge of the different possible environments, the designer has the freedom to select the suitable number and architecture of the models and controllers along with their parameter vectors. The designer might use fixed models or adaptive models or a combination of the two [138]. Using fixed models makes computations easier while it is generally cumbersome with adaptive models. However a single adaptive model may be sufficient for reconfiguration as compared to a large number of different fixed models. The choice about the structure and number of models is made off-line depending upon the prior knowledge about the plant and its parameters. In this thesis, all fixed models are used for the MMST scheme.

8.3.4 Stability analysis of MMST

[141] discusses the stability of the MMST technique. The following cases are discussed:

1. If all models are adaptive, the overall stability is guaranteed for any of the stated switching schemes, but a fixed but arbitrarily small interval is allowed between switches. This allows the designer to choose any of the switching schemes for MMST.
2. If all the models are fixed, and the performance index no. 4 is used and at least one of the fixed models has to be "sufficiently close" to the plant depending upon the plant parameters, stability is assured.
3. By using a mixture of fixed and adaptive models, the overall system is stable with zero steady state error. Nonetheless, a sufficiently large number of fixed models still has to be determined off-line for satisfactory transient response

8.4 Linear Quadratic Gaussian (LQG) Regulator

8.4.1 LQG-An overview

In the feedback gain control of SISO systems, a unique feedback gain is obtained, provided that the system is controllable. On the other hand no unique feedback gain is obtained for MIMO systems, so additional design freedom is available which can be utilized to obtain good trade-offs between robustness, performance, and control effort. Optimal Control Theory is used in such cases to resolve these issues and obtain good performance and efficient results. One such technique of optimal controls is the Linear Quadratic Gaussian (LQG) control. In this type of optimal control instead of specifying the exact value of the desired closed loop eigenvalues, a performance objective function is specified. The LQG controller has two cases; the finite time horizon and the infinite time horizon case.

The basic motivation of moving on to LQG controllers from Linear Quadratic Regulators (LQR) is that in most practical scenarios, all of the states are not available at the output at all of the time instants. Thus the assumption of the availability of the states in LQRs is not very pragmatic. Also in most environments, measurement and process noise corrupt the systems. So the effect of the noise must also be catered for when designing optimal controllers. Both the above stated issues can be solved by using LQG regulators instead of LQRs. The LQG design has two basic steps which can be performed independently of each other:

1. Estimate the states using the available information by employing a Kalman Filter.
2. Apply the LQR design using the estimated state vector $\hat{x}(t)$.

Kalman filter design:

The system dynamics are:

$$\dot{x}(t) = Ax(t) + Bu(t) + w(t) \tag{8.3}$$

$$y(t) = Cx(t) + Du(t) + v(t) \tag{8.4}$$

Where $w(t), v(t)$ depict the process and measurement noise respectively. In most cases these noise vectors are supposed to be white noise and have a zero mean and uncorrelated Gaussian distributions that is:

$$E[w(t)] = E[v(t)] = 0 \tag{8.5}$$

$$E[w(t)v^T(t)] = 0 \tag{8.6}$$

The covariance matrices of both noise vectors are assumed to be known:

$$E[w(t)w^T(t)] = Q \tag{8.7}$$

$$E[v(t)v^T(t)] = R \tag{8.8}$$

Also:

$$\hat{x}_0(0) = E[x_0(0)] \tag{8.9}$$

$$P_0(0) = E[\hat{e}_0(0)\hat{e}_0^{\ T}(0)] \tag{8.10}$$

Where $P_0(0)$ is the error covariance at $t = 0$.

The discrete Kalman Filter works using two steps; the predictor and the corrector steps to produce estimates of the states. No distinction exists between these two steps in the continuous case [143]. Since this thesis involves working in the continuous time, so this case is explained here. For the continuous time Kalman Filter, the state estimate and the covariance have the following differential equation:

$$\dot{\hat{x}}(t) = A\hat{x}(t) + Bu(t) + K(y(t) - C\hat{x}(t)) \tag{8.11}$$

$$\dot{P}(t) = AP(t) + P(t)A^T - K(t)R^{-1}K(t) + Q \tag{8.12}$$

Where K is the Kalman gain matrix given as:

$$K = P(t)C^T(t)R^{-1} \tag{8.13}$$

The differential equation for the covariance matrix $P \geq 0$ is actually the continuous time Algebraic Riccati Equation (CARE).

LQR design:

For the LQR design, the cost function that is minimized is:

$$J = \int_0^\infty (x^T(t)Qx(t) + u^T(t)Ru(t))dt \tag{8.14}$$

The matrices Q, R present the trade-off between control effort and performance. Q is added to penalize the state $x(t)$ and R penalizes the control effort $u(t)$. The feedback control achieved on minimizing the cost function in (8.14) is:

$$u(t) = -L\hat{x}(t) \tag{8.15}$$

Where $L = R^{-1}B^TP$ is the LQR's optimal gain matrix and $P \in \mathbb{R}^{n \times n} \geq 0$ is obtained by solving the Algebraic Riccati Equation (ARE).

$$0 = PA + A^T P - PBR^{-1} B^T P + Q \tag{8.16}$$

The above ARE is solvable only when (A, B) pair is controllable and (Q, R) pair is detectable.

8.4.2 MMST scheme with LQG

In this paper the LQG control method is employed as a basic control law within the framework of MMST scheme for reconfiguration. A bank of four different models pertaining to the four different actuator fault scenarios; no fault, abrupt, incipient and intermittent fault along with their respective suitable LQG controllers is pre-designed. Each of these model + controller pertains to a specific fault condition. At each time step, an appropriate switching index is computed and the model with the lowest value of this index is selected and the corresponding controller is switched on for reconfiguration. This method is simple yet efficient and robust for a broad range of flight conditions and is hence applied in this research.

CHAPTER 9: MATHEMATICAL MODELLING OF UAVs

This chapter provides an outline of the fundamentals of flight mechanics for aerial vehicles which will help in understanding and using the mathematical model of the Aerosonde UAV as a benchmark for testing the developed robust FTC scheme for actuator faults.

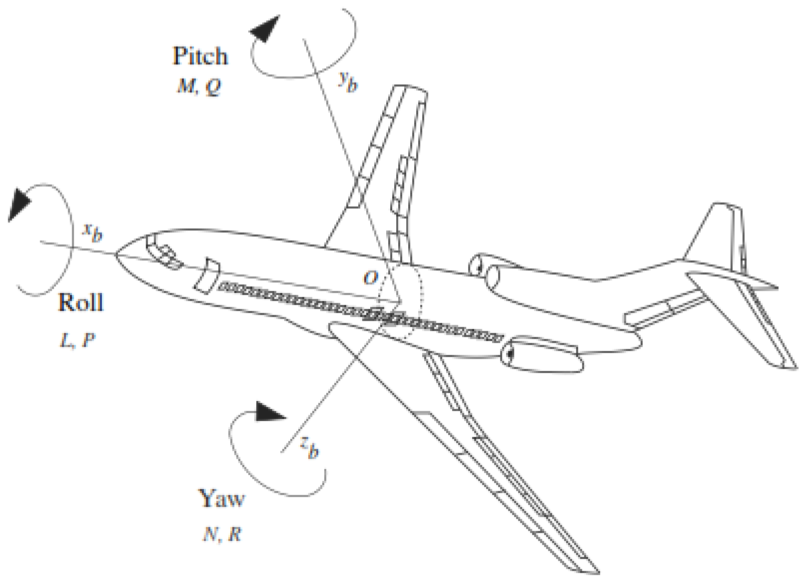

Figure 9.1: Aircraft body axis system

9.1 Airplane Flight Mechanics

Figure 9.1 taken from [143] shows the body axis system of an aircraft. The centre of gravity of the aircraft is taken as the origin of the axes which are the roll axis x_b, pitch axis y_b and yaw axis z_b. The rotation rates about these axes are the roll rate p, pitch rate q and the yaw rate r while the moments about these axes are the roll moment L, pitch moment M and the yaw moment N. The deflections of the control surfaces; aileron, elevator and rudder, control the roll, pitch and yaw rates respectively by changing the curvature of a wing or tail surface, the aircraft's lift, and its moment about the corresponding body axis. It is to be noted however that the yawing and rolling motions are coupled and not pure unlike the pitching motion. Newton's laws are used for the analysis of airplane motions in the development of flight mechanics and the airplane is considered as a rigid body. The important aircraft parts are displayed in Figure 9.2 [144].

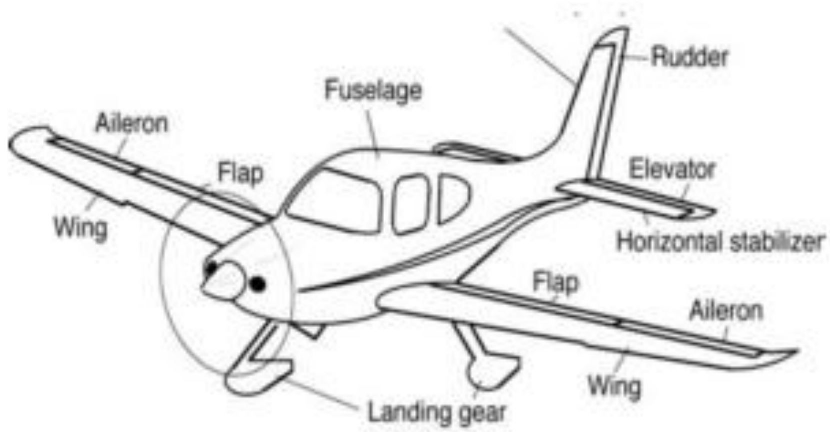

Figure 9.2: Important aircraft parts

9.2 Forces Acting on the Aircraft

The forces acting on an aircraft are illustrated in the Figure 9.3 and are explained below [145]:

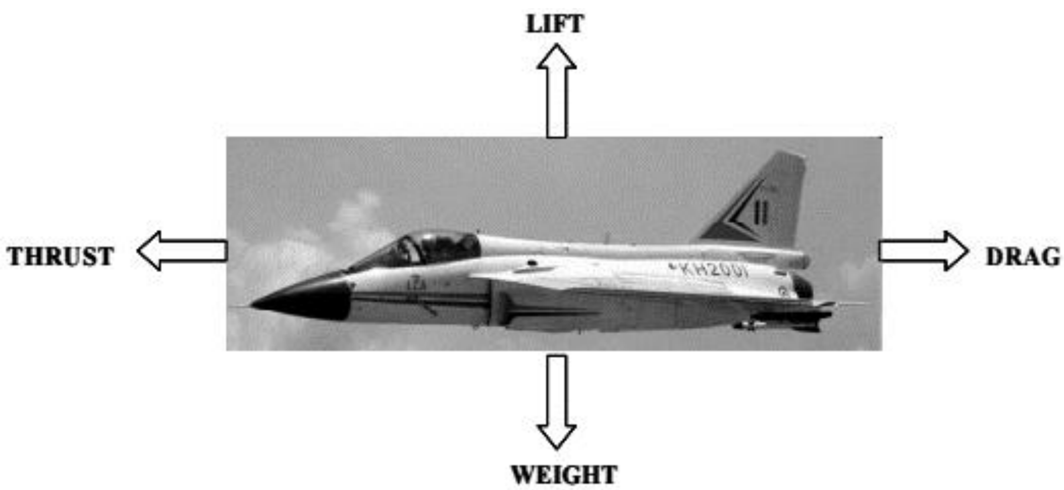

Figure 9.3: Forces acting on an aircraft

9.2.1 Lift

The upward force which elevates up and sustains the aircraft in flight is called the lift. Lift force, caused by the air flow, depends upon the wing shape. The aircraft ascends only when the lift force becomes greater than the aircraft's weight.

9.2.2 Weight

The downward force which includes the weight of the aircraft along with the load is called the weight. It is directly proportional to the upward lift force. When the weight becomes greater than the aircraft's lift force, the aircraft descends.

9.2.3 Thrust

Thrust is the force exerted by the aircraft's engines which pushes the air backwards and causes a reaction force to move the aircraft in the forward direction.

9.2.4 Drag

The drag force is opposition to the thrust and causes a resistance to the aircraft's forward motion. The drag of the air makes reduces the speed of the aircraft. Drag is also called air resistance. It is caused by all the parts.

9.3 Equations of Motion in 6DOF

Since the Newton's laws of motion are effective only in an inertial frame of reference which is not accelerating or rotating, for airplane motion, the earth is considered as an approximate inertial frame of reference, and this aerodynamic model is termed as the "flat earth model", which may give small errors in analysis. The following equations govern the translational and rotational motion of an airplane:

1. Equations which provide the translational and rotational position of the aircraft relative to the earth reference frame called the Kinematic equations.
2. Equations which relate the corresponding forces to translational acceleration and moments to rotational acceleration known as the Dynamic equations.
3. Equations describing the variable-mass features of the airplane (centre of gravity, mass and moments of inertia) versus time.
4. Equations which provide the positions of the control surfaces and other movable parts of the airplane such as landing gear, flaps, wing sweep, etc. versus time.

The above equations are together called the "Six Degree of Freedom (6DOF) equations of motion." The 6DOF equations are used depending upon the specific arena of flight mechanics being analysed and inspected. These equations are non-linear are further linearized for simplicity by an appropriate method of linearization.

9.3.1 Non-linear equations of motion

The non-linear mathematical model of UAV consists of 15 differential equations which are summarized below [145]:

Position Equations:

$$
\begin{aligned}
\dot{x} &= u\cos\theta\cos\phi + v(-\cos\phi\sin\psi + \sin\theta\cos\psi) + w(\sin\phi\sin\psi + \cos\phi\sin\theta\cos\psi) \\
\dot{y} &= u\cos\theta\sin\psi + v(\cos\phi\cos\psi + \sin\theta\sin\psi) + w(\sin\phi\cos\psi + \cos\phi\sin\theta\sin\psi) \\
\dot{z} &= u\sin\theta - v(\sin\phi\cos\theta\sin\psi) - w(c\mathrm{os}\theta\cos\theta)\dot{h}
\end{aligned}
\tag{9.1}
$$

Velocity Equations:

$$
\begin{aligned}
\dot{u} &= rv - wq - g\sin\theta + \left(\frac{T + D\cos\alpha\cos\beta - L\sin\alpha - Y\cos\alpha\sin\beta}{M}\right) \\
\dot{v} &= -ru - wq - g\sin\phi\cos\theta + \left(\frac{D\sin\beta + Y\cos\beta}{M}\right) \\
\dot{w} &= ru - wq - g\sin\theta + \left(\frac{T + D\cos\alpha\cos\beta - L\sin\alpha - Y\cos\alpha\sin\beta}{M}\right)
\end{aligned}
\tag{9.2}
$$

Moment Equations:

$$
\begin{aligned}
\dot{p} &= I_z l + xI_{xz} n + I_{xz}(I_x - I_z + I_y)pq + \frac{(I_z I_y - I_z^2 - I_{xz}^2 qr)}{(I_x I_z - I_{xz}^2)} \\
\dot{q} &= m - pr(I_x - I_z) - I_{xz}\frac{(p^2 - r^2)}{(I_y)} \\
\dot{r} &= I_{xz} l + I_x n + (I^2{}_x - I_y I_x)pq - I_{xz}\frac{(I_z - I_y + I_x)pr}{(I_x I_z - I^2{}_{xz})}
\end{aligned}
\tag{9.3}
$$

Kinematic Equations:

$$
\begin{aligned}
\dot{\phi} &= p + \tan\theta + q\sin\phi + r\cos\phi \\
\dot{\theta} &= q\cos\phi - r\sin\phi \\
\dot{\psi} &= \frac{(q\sin\phi + r\cos\phi)}{\cos\theta}
\end{aligned}
\tag{9.4}
$$

Wind Axes Equations:

$$\begin{bmatrix} \dot{u} \\ \dot{\alpha} \\ \dot{q} \\ \dot{\theta} \\ \dot{h} \end{bmatrix} = \begin{bmatrix} X_u & X_\alpha & 0 & -g & 0 \\ \dfrac{Z_u}{u_0 - Z_{\dot{\alpha}}} & \dfrac{Z_\alpha}{u_0 - Z_{\dot{\alpha}}} & \dfrac{u_0}{u_0 - Z_{\dot{\alpha}}} & 0 & 0 \\ M_u & M_\alpha & M_q & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & -u_0 & 0 & u_0 & 0 \end{bmatrix} \begin{bmatrix} u \\ \alpha \\ q \\ \theta \\ h \end{bmatrix} + \begin{bmatrix} X_{\delta_e} \\ Z_{\delta_e} \\ M_{\delta_e} \\ 0 \\ 0 \end{bmatrix} \delta_e \tag{9.5}$$

Where x, y, z is the translational position components of the aircraft in the three axes in geographical coordinate system, u, v, w are the translational velocity components in body frame, θ, ϕ, ψ are pitch, roll and yaw attitude angles respectively, h is the airplane's altitude above sea level, p, q, r are rolling, pitching and yawing moments in body frame, α is the angle of attack and β is the sideslip angle, V is the velocity of the airplane relative to the ground, T is the thrust of engine, M is the mass of the UAV, I_x, I_y, I_z are the moments of inertia while I_{xz}, I_{xy}, I_{yz} are the products of these moments. D is the drag, L is the lift and Y is the side-force given as follows:

$$\begin{aligned} D &= QSC_D \\ L &= QSC_L \\ Y &= QSC_Y \end{aligned} \tag{9.6}$$

Where Q is the dynamic pressure, S is the reference wing area. l, m, n are the moments about the three axis and are computed as follows:

$$\begin{aligned} l &= QSBC_1 \\ m &= QSCC_m \\ n &= QSBC_n \end{aligned} \tag{9.7}$$

Where $C_D, C_L, C_Y, C_l, C_m, C_n$ are the drag, lift, side force and rolling, pitching and yawing coefficients of moment respectively. These coefficients may be computed as follows:

$$
\begin{aligned}
C_D &= C_{DO} + C_D^{\alpha} + \frac{C_D^{q} QC}{2V} + \frac{C_D^{\dot{\alpha}} \dot{\alpha} C}{2V} + \frac{C_D^{u} u}{V} + C_D^{\delta_e} \delta_e \\
C_Y &= C_Y^{\beta} \beta + \frac{C_Y^{p} pb}{2V} + \frac{C_Y^{r} rb}{2V} + C_Y^{\delta_\alpha} \delta_\alpha + C_Y^{\delta_r} \delta_r \\
C_L &= C_{L0} + C_L^{\alpha} \alpha + \frac{C_L^{q} QC}{2V} + \frac{C_L^{\dot{\alpha}} \dot{\alpha} C}{2V} + C_L^{\delta_e} \delta_e \\
C_l &= C_l^{\beta} \beta + \frac{C_l^{p} pb}{2V} + \frac{C_l^{r} rb}{2V} + C_l^{\delta_\alpha} \delta_\alpha + C_l^{\delta_r} \delta_r \\
C_m &= C_{m0} + C_m^{\alpha} \alpha + \frac{C_m^{q} QC}{2V} + \frac{C_m^{\dot{\alpha}} \dot{\alpha} C}{2V} + \frac{C_m^{u} u}{V} + C_m^{\delta_e} \delta_e \\
C_n &= C_n^{\beta} \beta + \frac{C_n^{p} pb}{2V} + \frac{C_n^{r} rb}{2V} + C_n^{\delta_\alpha} \delta_\alpha + C_n^{\delta_r} \delta_r
\end{aligned}
\tag{9.8}
$$

Where δ_a, δ_e and δ_r are the aileron, elevator and rudder deflections, measured in radians, respectively. The values and description of the other parameters used in (9.8) can be obtained from [145].

9.3.2 Aircraft dynamic models

The behaviour of an aircraft after its steady non-oscillating flight has been disturbed can be illustrated through the dynamic models; the longitudinal and lateral directional models [146]. The disturbed oscillating motions of the aircraft are described by two parameters; the oscillation time period and the time taken by the amplitude of the unstable motion to be damped to half or increased to double. There longitudinal directional model comprises of the "phugoid mode" which has a longer period and a short period mode. In the phugoid mode, the variations in the amplitudes of altitude, air-speed and pitch angle are large but there is almost no variation in the angle-of-attack. On the other hand, in the short period mode there is typically a pitching oscillation which is heavily damped and has a period of only a few seconds. The speed does not change, only the angle-of-attack varies.

In the lateral directional mode, rolling and yawing motions are coupled into each other. There can be three kinds or modes of lateral directional dynamic motions: roll subsidence mode, spiral mode, and Dutch roll mode. Roll subsidence mode involves the damping of the rolling motion and the combined rolling and yawing motion is the Dutch roll mode. It may be added that spiralling is an inherent oscillatory motion for the lateral directional model.

9.3.3 Linear equations of motion

The 6DOF non-linear mathematical model of UAV may be linearized about a nominal point to simply the model. The linearized longitudinal and lateral directional state space models [147] of the UAV are given below in (9.9), (9.10) respectively:

$$\begin{bmatrix} \dot{u} \\ \dot{\alpha} \\ \dot{q} \\ \dot{\theta} \\ \dot{h} \end{bmatrix} = \begin{bmatrix} X_u & X_\alpha & 0 & -g & 0 \\ \frac{Z_u}{u_0 - Z_{\dot{\alpha}}} & \frac{Z_\alpha}{u_0 - Z_{\dot{\alpha}}} & \frac{u_0}{u_0 - Z_{\dot{\alpha}}} & 0 & 0 \\ M_u & M_\alpha & M_q & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & -u_0 & 0 & u_0 & 0 \end{bmatrix} \begin{bmatrix} u \\ \alpha \\ q \\ \theta \\ h \end{bmatrix} + \begin{bmatrix} X_{\delta_e} \\ Z_{\delta_e} \\ M_{\delta_e} \\ 0 \\ 0 \end{bmatrix} \delta_e \quad (9.9)$$

$$\begin{bmatrix} \dot{\beta} \\ \dot{p} \\ \dot{r} \\ \dot{\phi} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} \frac{Y_p}{u_0} & g\cos\theta & \frac{Y_\beta}{u_0} & \frac{Y_r - u_0}{u_0} & 0 \\ L_p & 0 & L_\beta & L_r & 0 \\ 1 & 0 & 0 & 0 & 0 \\ N_p & 0 & N_\beta & N_r & 0 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \beta \\ p \\ r \\ \phi \\ \psi \end{bmatrix} + \begin{bmatrix} Y_{\delta_a} & Y_{\delta_r} \\ L_{\delta_a} & L_{\delta_r} \\ 0 & 0 \\ N_{\delta_a} & N_{\delta_r} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_a \\ \delta_r \end{bmatrix} \quad (9.10)$$

9.4 Aerosonde UAV

The Aerosonde is a small-class commercial UAV. It is mainly used for meteorological purposes especially collecting weather data. It was originally designed and developed by Insitu Inc. which is an American company. Later on the Australian based UAV Company "Aerosonde Ltd.," which is a subsidiary of the "AAI Corporation" started manufacturing the Aerosonde UAV [148]. The Aerosonde UAV is a fixed wing aircraft and some of its specifications may be found in [149].

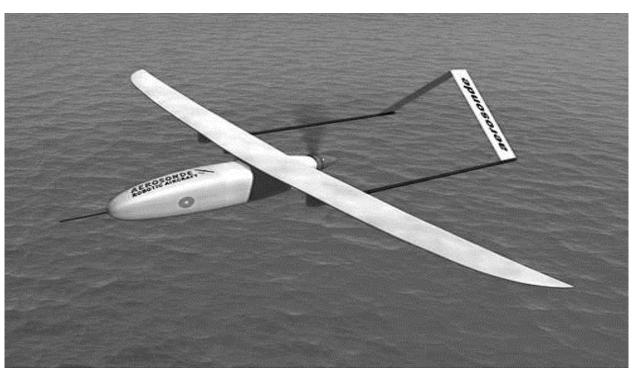

Figure 9.4: Aerosonde UAV

CHAPTER 10: SIMULATIONS AND RESULTS

After the development of the FTC scheme, its efficiency and robustness is tested by applying it on a linearized lateral directional model of the Aerosonde UAV found in [150]. This chapter provides the mathematical model of the Aerosonde UAV, inputs, requirements and results of the MATLAB simulations of the FTC technique.

10.1 State Space Model of Aerosonde UAV

FTC scheme is designed and analysed in the Simulink/ MATLAB environment using the following state space matrices:

$$A = \begin{bmatrix} -0.64 & 1.51 & 22.95 & -9.78 & 0 \\ -4.19 & -20.63 & 9.93 & 0 & 0 \\ 0.68 & -2.68 & -1.04 & 0 & 0 \\ 0 & 1.00 & 0 & 0 & 0 \\ 0 & 0 & 1.00 & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} -1.25 & 3.19 \\ -109.84 & 1.98 \\ -4.33 & -20.17 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}$$

$$C = \begin{bmatrix} 0.04 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

$$D = 0_{5\times2}$$

The state vector of the lateral directional model for the Aerosonde UAV is:

$$x = \begin{bmatrix} v \\ p \\ r \\ \phi \\ \psi \end{bmatrix}$$

Where $v =$ translational velocity in y-axis, $p =$ roll rate, $r =$ yaw rate, $\phi =$ roll angle and $\psi =$ yaw angle.

10.2 Addition of Disturbances and Noise in the Aerosonde UAV State Space Model

In order to cater for the disturbance and model uncertainties faced by the UAV in the practical environment, these are introduced in the state space model in the form of the following disturbance matrix:

$$E = 15 \times \begin{bmatrix} 1 & 1 \\ 1 & 1 \\ 1 & 1 \\ 1 & 1 \\ 1 & 1 \end{bmatrix}$$

The noise encountered by the system is selected as Gaussian noise with mean=0 and 0.1 variance.

10.3 Inputs and Outputs of the Aerosonde UAV State Space Model

The input signals vector $u(t) = \begin{bmatrix} \delta_a \\ \delta_r \end{bmatrix}$, $\delta_a =$ aileron deflection and $\delta_r =$ rudder deflection is simulated as a step function of 5 radians amplitude as displayed in Figure 10.1.

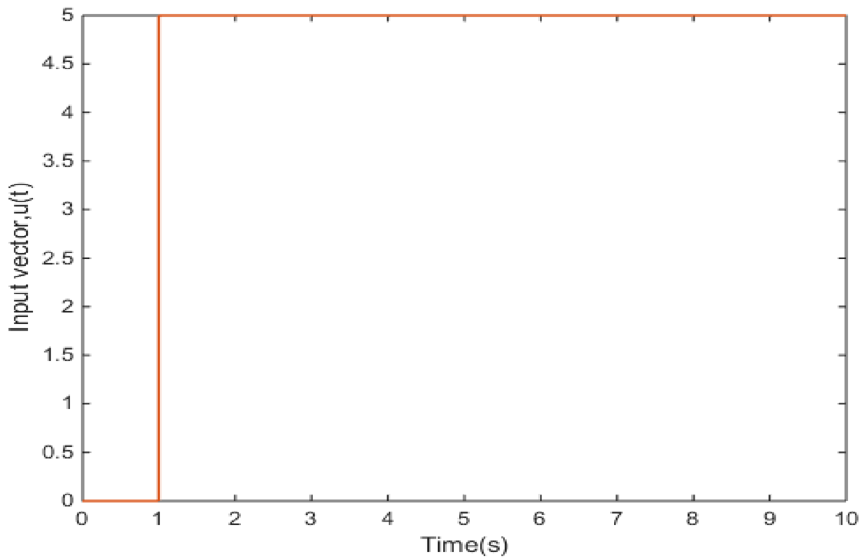

Figure 10.1: Input vector

At the output, we have the vector:

$$y = \begin{bmatrix} \beta \\ p \\ r \\ \phi \\ \psi \end{bmatrix}$$

Where $\beta =$ sideslip angle.

10.4 Actuator Faults introduced in the Aerosonde UAV State Space Model

The three different type of actuator faults; abrupt, incipient and intermittent; are injected only at the first input as fault. The actuator faults are introduced at three different at simulation times to check the efficiency, accuracy and robustness of the proposed FTC technique: t=2, 5 and 7s as step functions of 0.3 amplitude, unit ramp and a unit pulsed signal with periods of 3 (for t=2s) and 2 seconds and pulse widths of 0.14s (for t=2s) 0.03s (for t=5s) and 0.08s (for t=7s) respectively. The different actuator faults introduced in the system at t=2s are shown below:

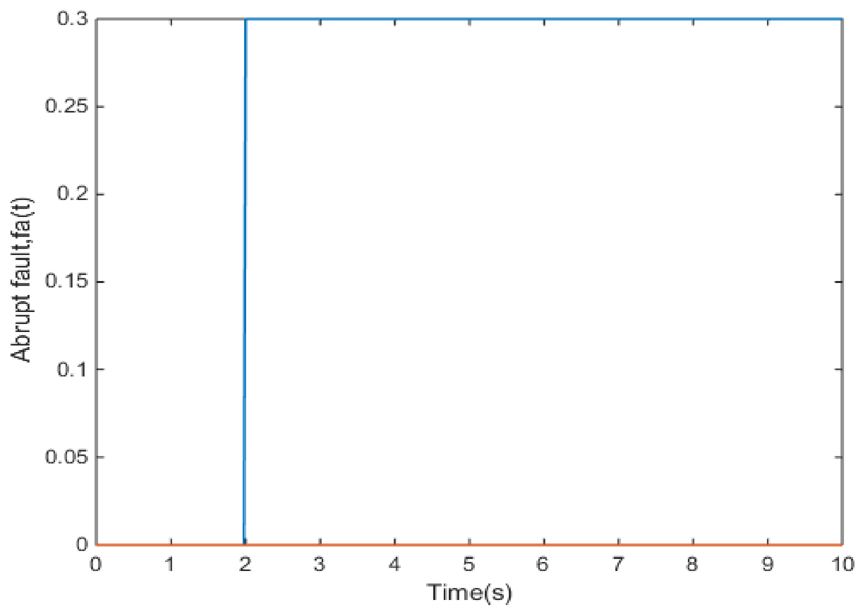

Figure 10.2: Abrupt actuator fault at t=2s

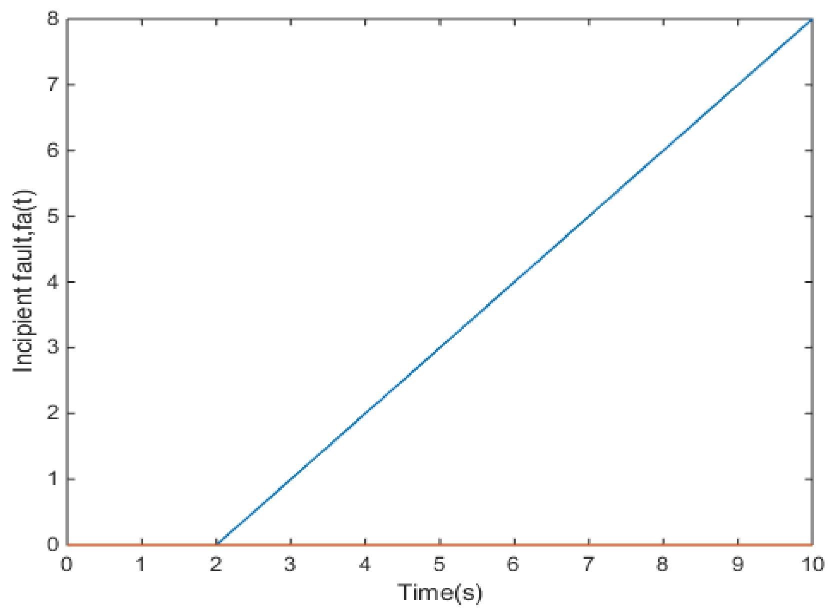

Figure 10.3: Incipient actuator fault at t=2s

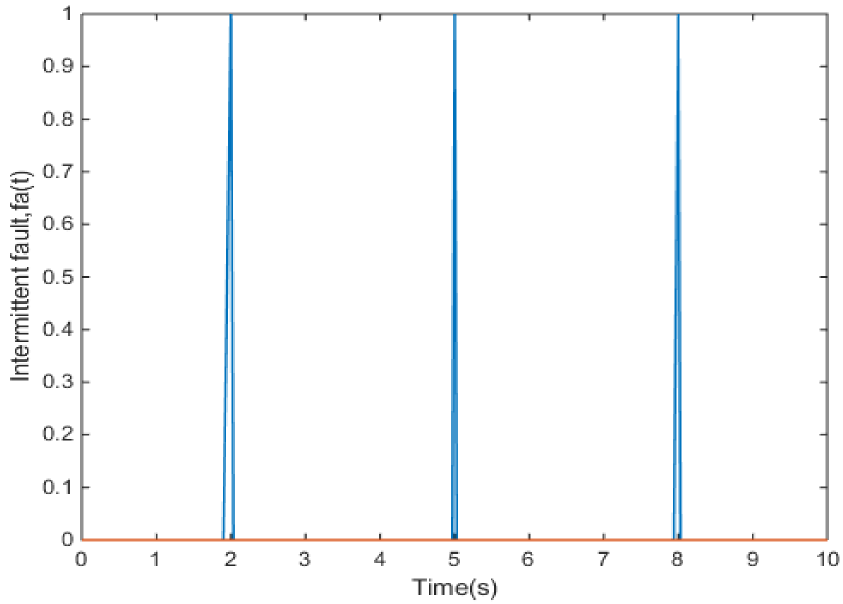

Figure 10.4: Intermittent actuator fault at t=2s

10.5 Application of the proposed FDI technique on the Aerosonde UAV State Space Model

The FDI is applied on the UAV model. The observer eigenvalues are set as $\left[-11.5397 \quad -19.4274 \quad -2.0692 \quad -0.9755 \quad -0.4240\right]$ and the eigenstructure assignment method is applied to ensure robustness. Figures 10.5-10.8 display the robust residuals generated by our FDI scheme. The disturbance decoupling is successfully achieved as shown in these plots.

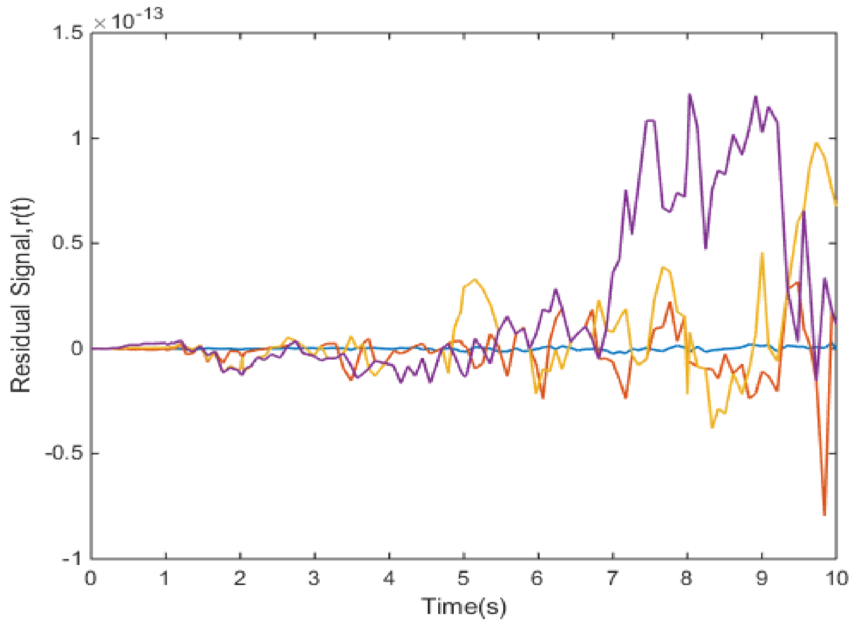

Figure 10.5: Residual signals generated when no faults are present

10.5.1 FDI for actuator faults at t=2s

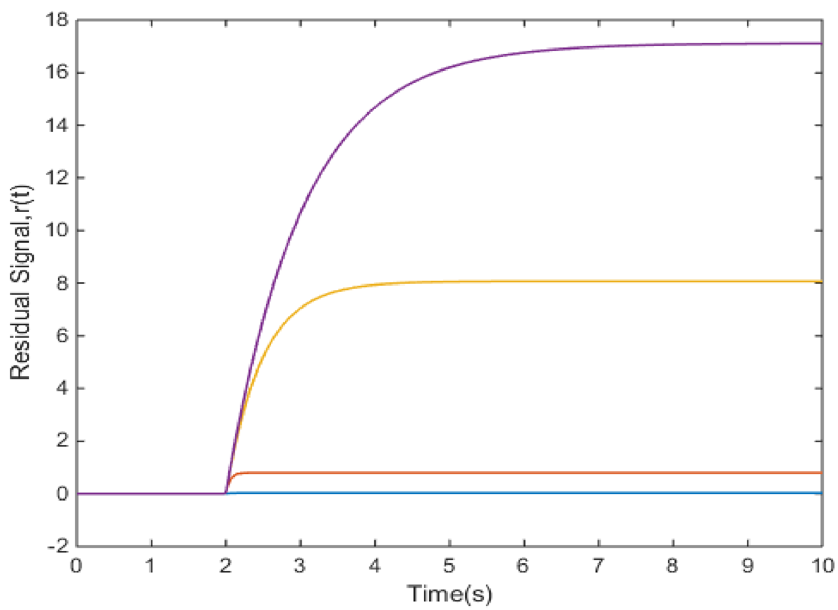

Figure 10.6: Residual signals generated when abrupt fault is present

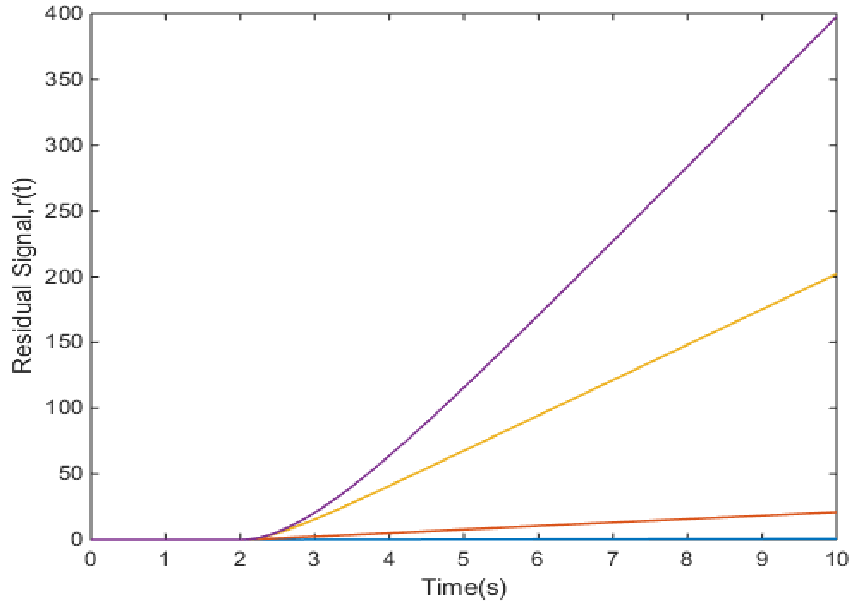

Figure 10.7: Residual signals generated when incipient fault is present

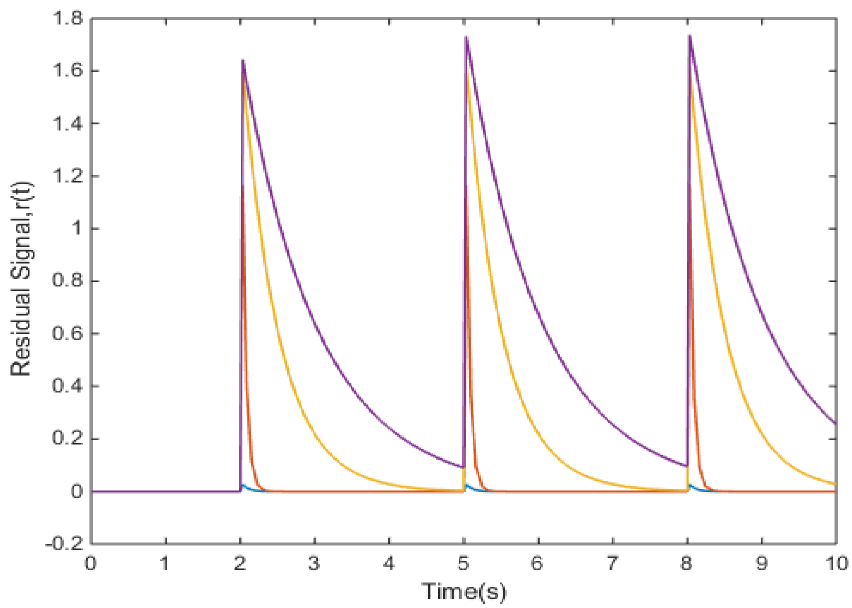

Figure 10.8: Residual signals generated when intermittent fault is present

After the residuals, SPRT is applied in Simulink. The error probabilities are $\alpha = \beta = 0.2$. The delays encountered while the detection of the actuator faults are enlisted in Table 10-1.

Table 10-1: Delays in actuator fault detection at t=2s

Actuator Fault at t=2s	Delay (in seconds)
Abrupt Fault	0.2312
Incipient Fault	0.3883
Intermittent Fault*	0.03, 0.03, 0.03

*For the intermittent type of fault, pulses occur at t= 2s, 5s and 8s.

The tabulated data proves that our FDI scheme experiences minimum delays in the detection of UAV actuator faults.

The FDI scheme is applied for the cases where actuator faults occur at t=5s and the results are displayed in the subsequent sections:

10.5.2 FDI for actuator faults at t=5s

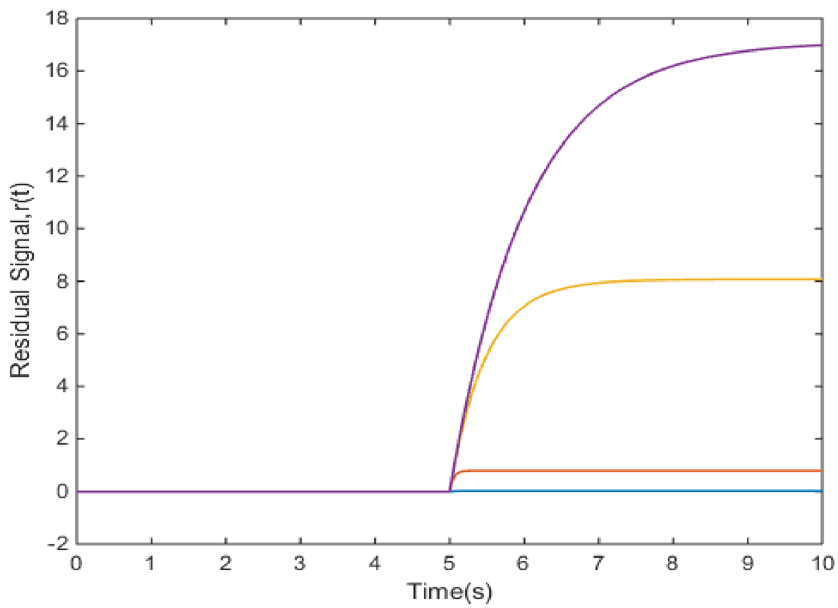

Figure 10.9: Residual signals generated when abrupt fault is present

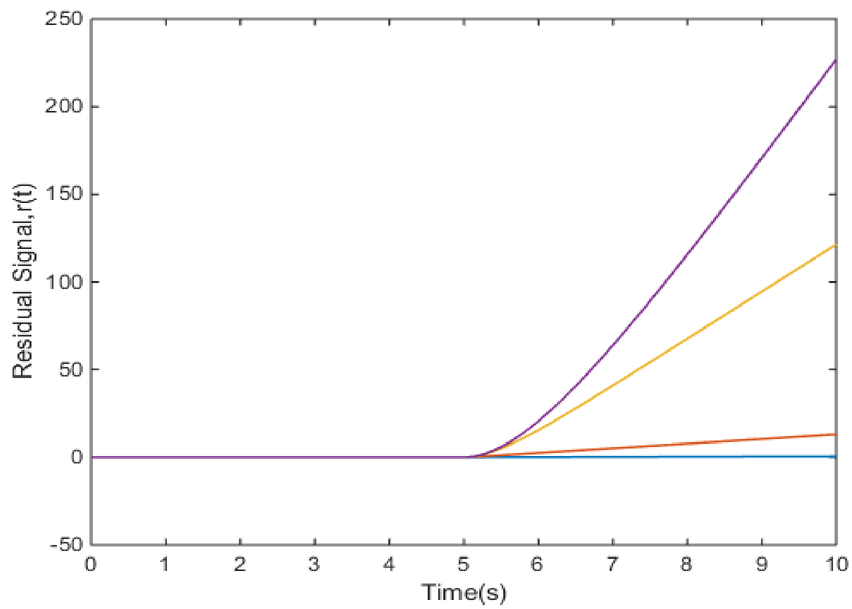

Figure 10.10: Residual signals generated when incipient fault is present

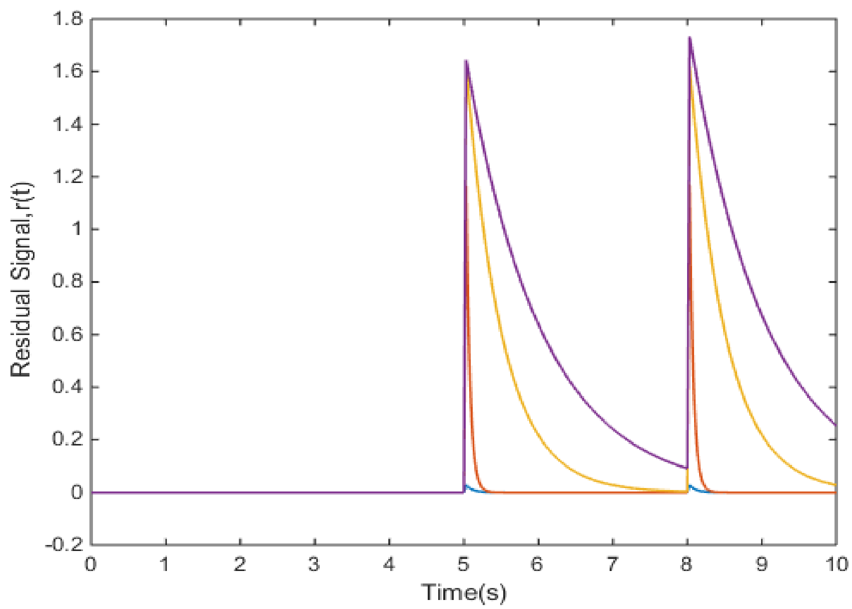

Figure 10.11: Residual signals generated when intermittent fault is present

Table 10-2: Delays in actuator fault detection at t=5s

Actuator Fault at t=5s	**Delay (in seconds)**
Abrupt Fault	0.1845

Incipient Fault	0.3996
Intermittent Fault*	0.0266, 0.0266

*For the intermittent type of fault, pulses occur at t= 5s and 8s.

10.5.3 FDI for actuator faults at t=7s

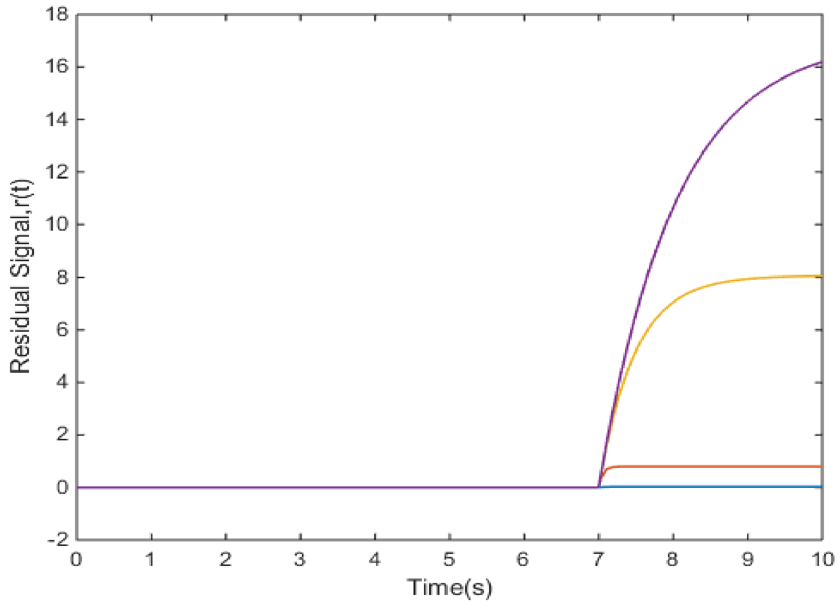

Figure 10.12: Residual signals generated when abrupt fault is present

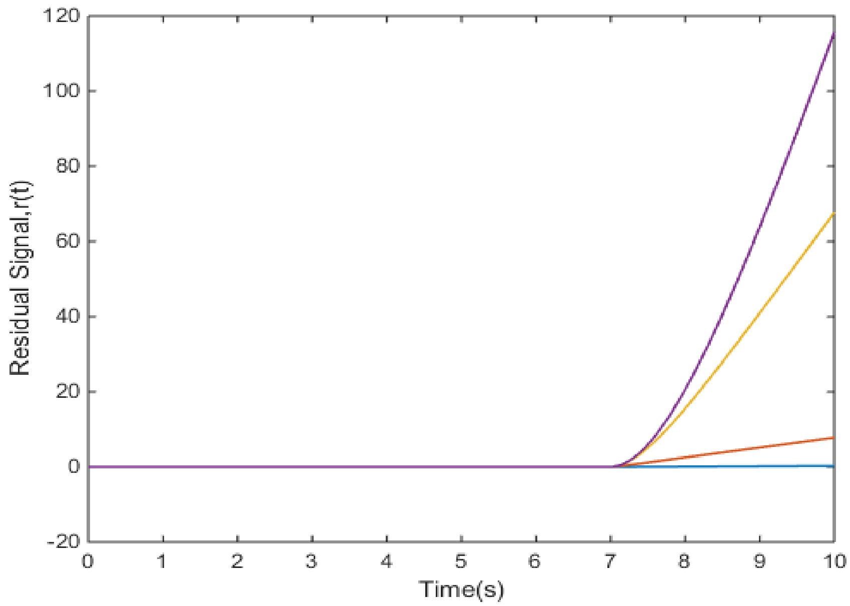

Figure 10.13: Residual signals generated when incipient fault is present

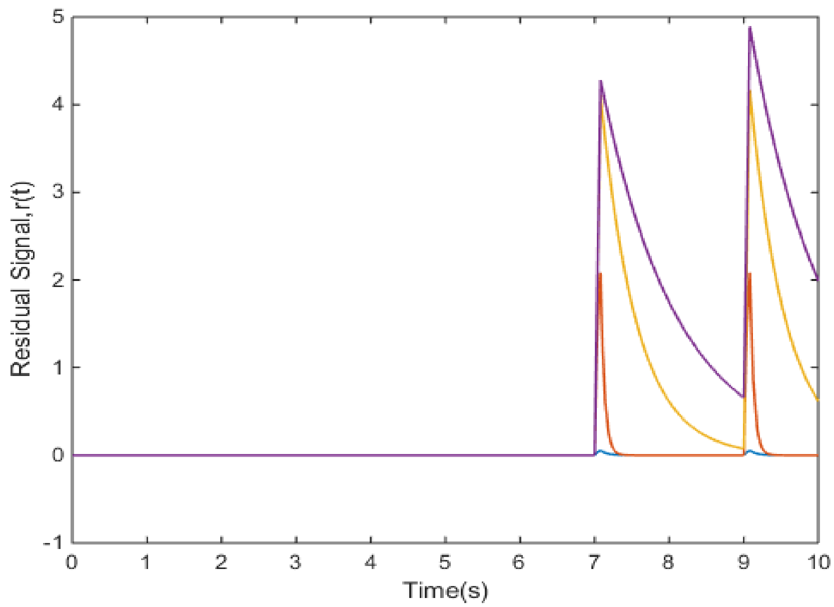

Figure 10.14: Residual signals generated when intermittent fault is present

Table 10-3: Delays in actuator fault detection at t=7s

Actuator Fault at t=5s	Delay (in seconds)
Abrupt Fault	0.1850
Incipient Fault	0.3788
Intermittent Fault*	0.0266, 0.0266

*For the intermittent type of fault, the pulses occur at t= 7s and 9s.

10.6 Application of the proposed Reconfiguration technique on the Aerosonde UAV State Space Model

The output regulation is achieved in the reconfiguration phase through the LQG based MMST approach. Each of the fault models has a different LQG (with different parameters). Figs 10.15-10.18 demonstrate the small regulation errors produced when our proposed reconfiguration technique is applied on the Aerosonde model.

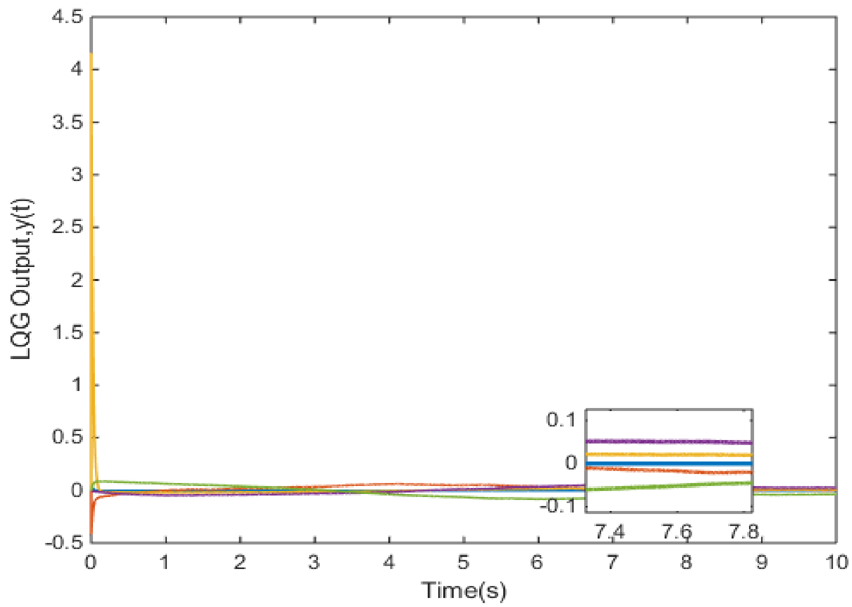

Figure 10.15: Output of LQG when no faults are present

10.6.1 Reconfiguration for actuator faults at t=2s

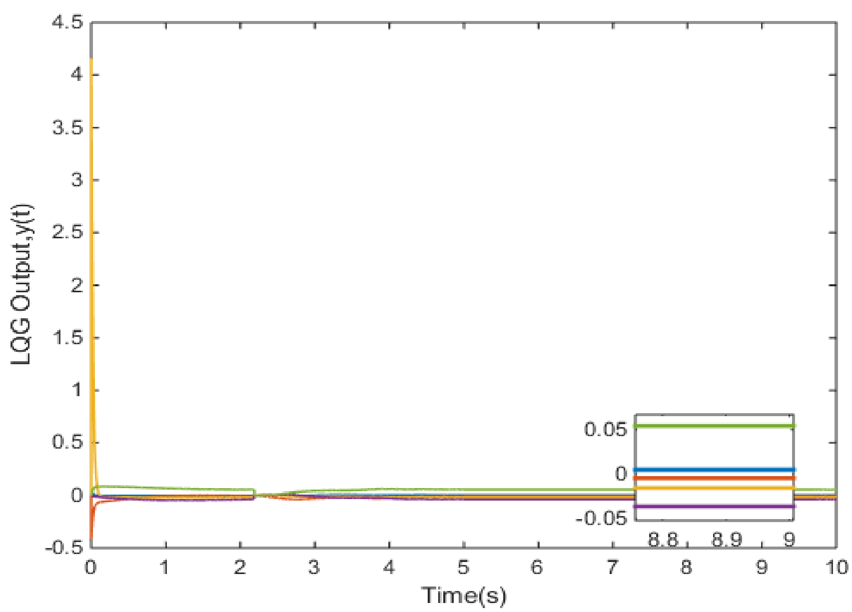

Figure 10.16: Output of LQG when abrupt fault is present

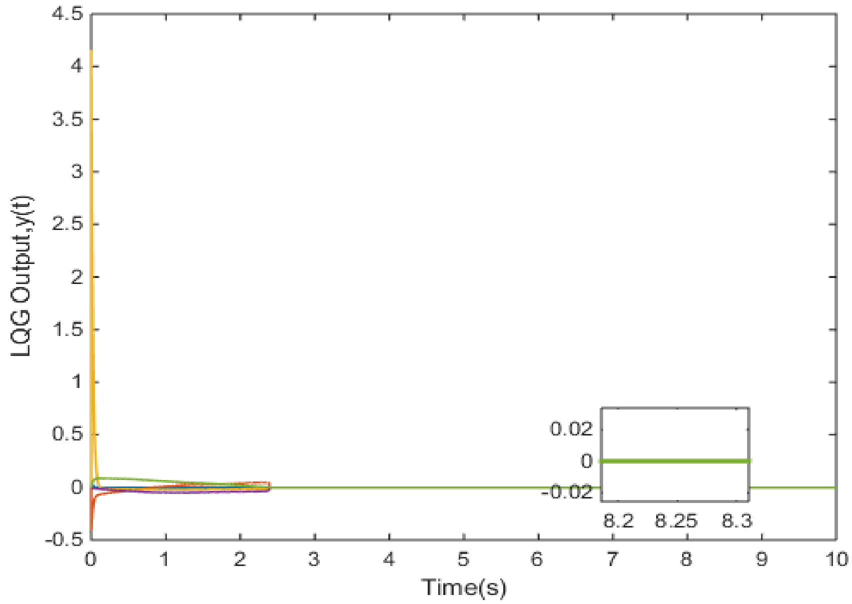

Figure 10.17: Output of LQG when incipient fault is present

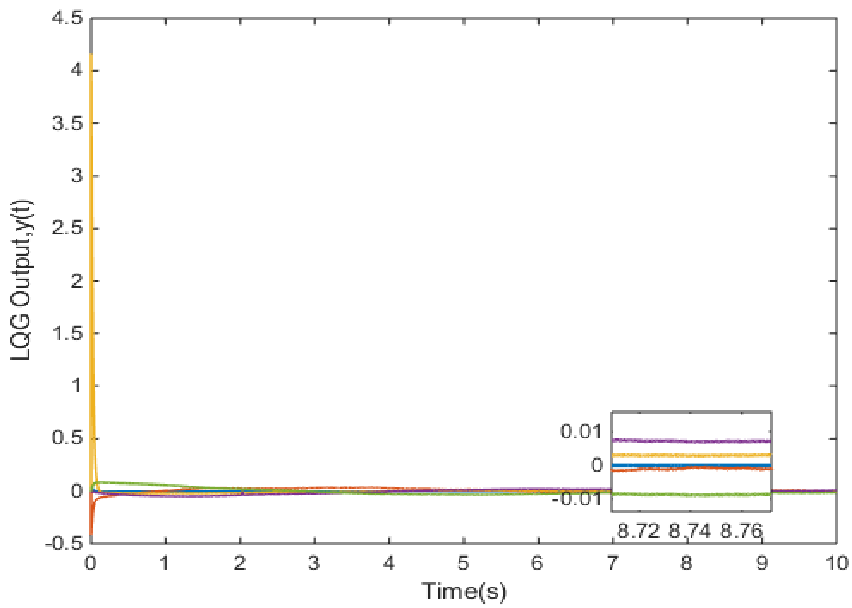

Figure 10.18: Output of LQG when intermittent fault is present

10.6.2 Reconfiguration for actuator faults at t=5s

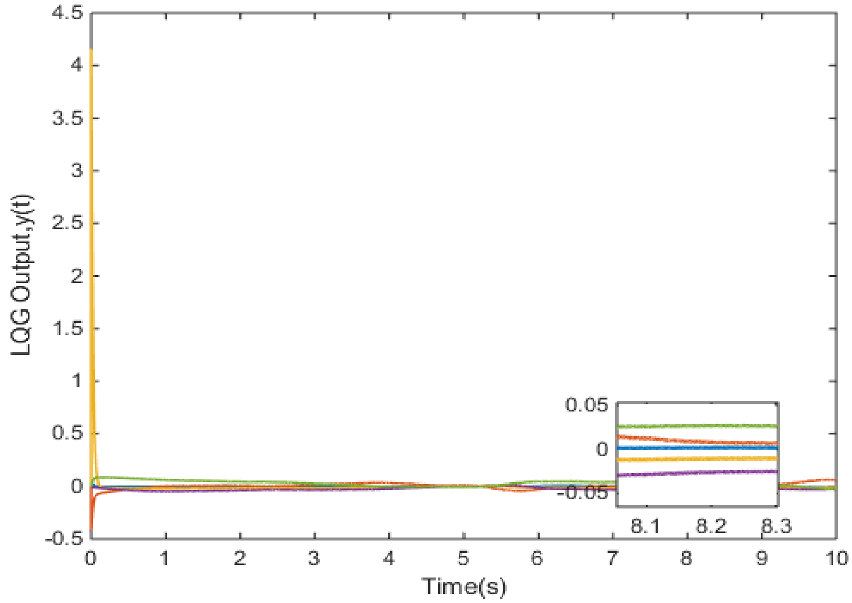

Figure 10.19: Output of LQG when abrupt fault is present

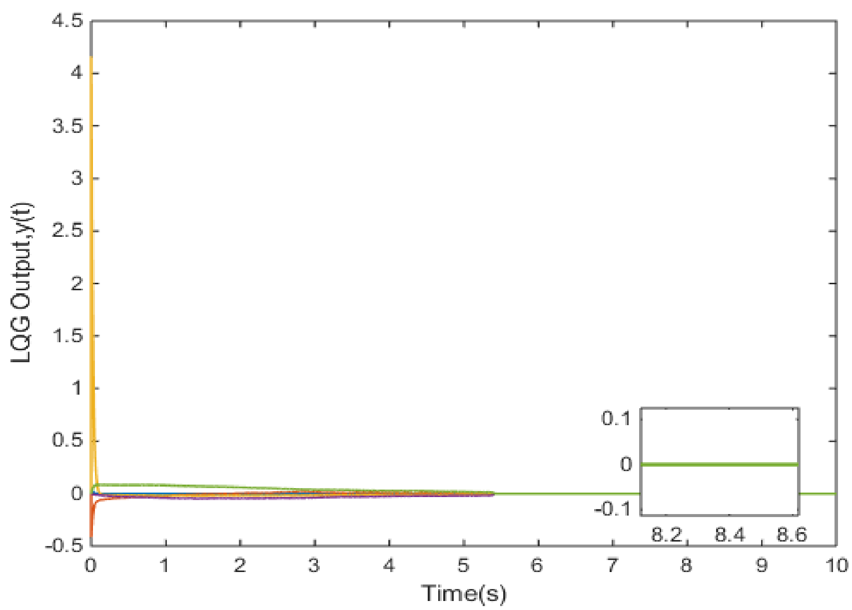

Figure 10.20: Output of LQG when incipient fault is present

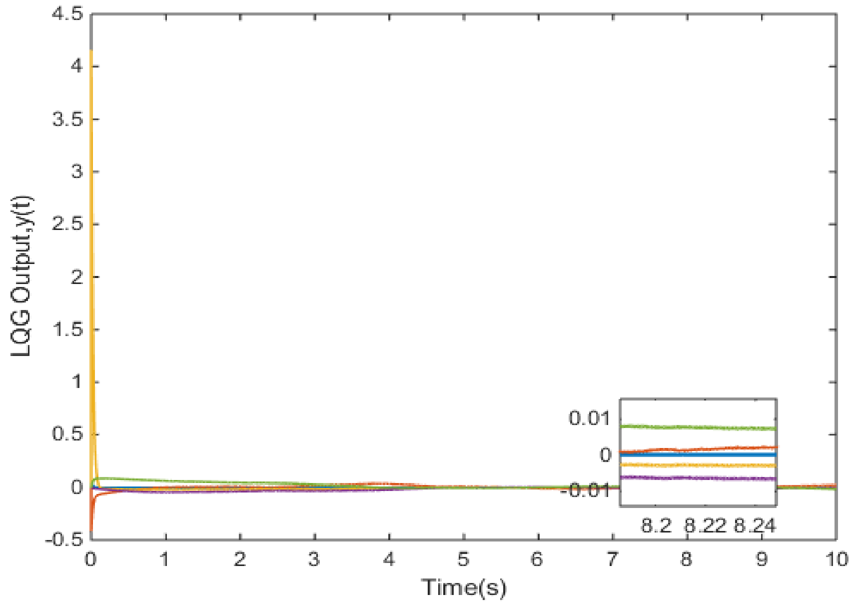

Figure 10.21: Output of LQG when intermittent fault is present

10.6.3 Reconfiguration for actuator faults at t=7s

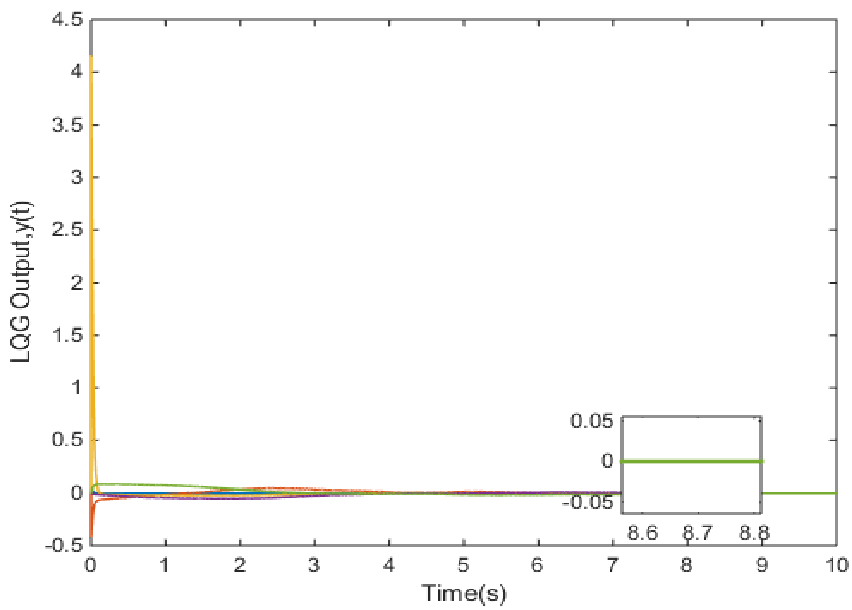

Figure 10.22: Output of LQG when abrupt fault is present

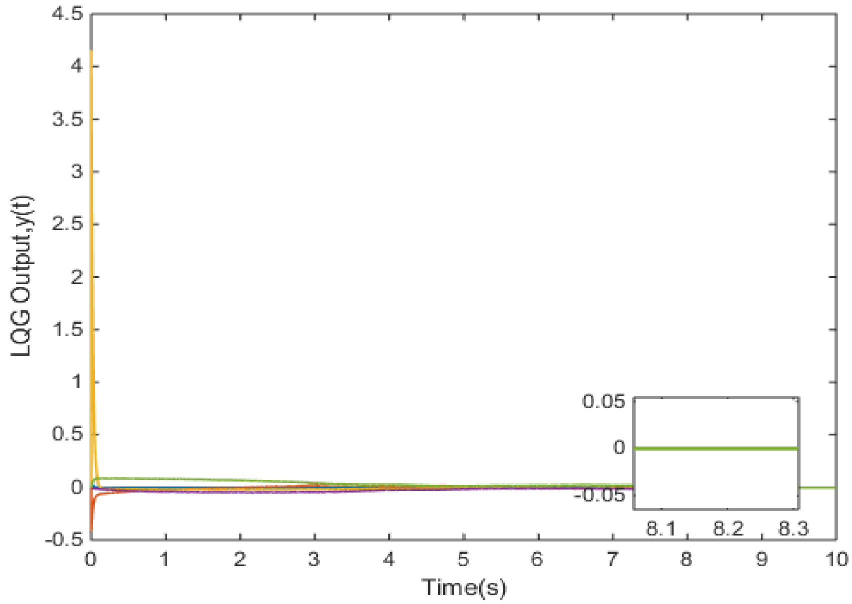

Figure 10.23: Output of LQG when incipient fault is present

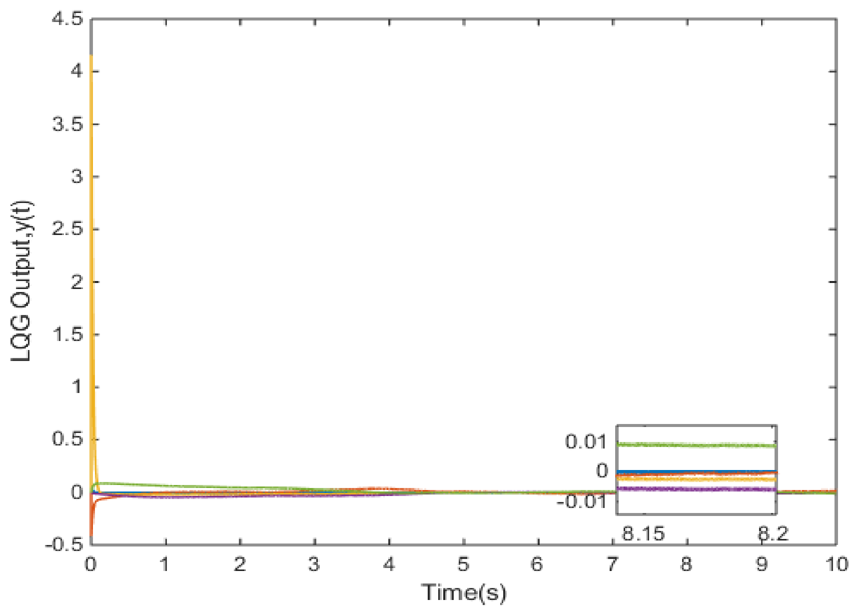

Figure 10.24: Output of LQG when intermittent fault is present

CHAPTER 11: CONCLUSIONS AND FUTURE SCOPE

This chapter puts forward the closing remarks and presents some recommendations which may be applied to further enhance and improve the work done in this research.

11.1 Conclusions

The control and navigation of UAVs almost always requires a robust FTC scheme to cater for the different faults experienced during flight and prevent failures and permanent instabilities. This thesis has developed and presented a robust FTC scheme for UAVs in the presence of three forms of actuator faults; abrupt, incipient and intermittent. The FTC scheme consists of robust FDI and reconfiguration steps. Full-state observer is used for FDI and the eigenstructure assignment method ensures the robustness of FDI. SPRT decides for the faults efficiently. For reconfiguration, the LQG based MMST technique is introduced. Subsequently, the claimed robustness and efficiency of our FTC system is demonstrated through simulations on a linearized lateral directional model of the Aerosonde UAV. This suggested FTC scheme, combining robust FDI with reconfiguration has not been implemented till date on the Aerosonde UAV model in this fashion, to the best of knowledge. Furthermore, the minimum detection times and small regulation errors illustrate and justify the efficiency, robustness and practicality of our developed FTC technique.

11.2 Future Work

This research opens up different avenues for future work and research on the FTC of UAVs. In this research, actuator faults are incorporated in the UAV model only at a single (first) input but in some practical environments, faults may occur at more than one input simultaneously. So for the future, fault isolation for multiple input actuator faults may be incorporated to enhance the proposed FTC scheme. A reference tracking scheme may be developed instead of a regulation one for the reconfiguration phase of the UAV FTC. As stated in Chapter 3, sensor and component faults also affect the UAVs during flight so the FTC technique developed in this thesis may be enhanced by making it to identify and cater for sensor and component faults along with the actuator faults. Finally a non-linear model and appropriate adjustments may also be applied as a future addition to this research work.

APPENDIX A

MATLAB CODE:

The MATLAB program used for the robust FTC of Aerosonde UAV is given below:

```
%
%% FTC FOR THE LATERAL DIRECTIONAL MODEL OF AEROSONDE
AIRCRAFT
close all;clear ;clc;
%% State Space Model for Aerosonde UAV
A=[-0.64 1.51 -22.95 9.78 0
   -4.19 -20.63 9.93 0 0
   0.68 -2.68 -1.04 0 0
   0 1.00 0 0 0
   0 0 1.00 0 0];
B=[-1.25 3.19
   -109.84 1.98
   -4.33 -20.17
   0 0
   0 0];
C=[0.04 0 0 0 0
   0 1 0 0 0
   0 0 1 0 0
   0 0 0 1 0
   0 0 0 0 1];
D=zeros(5,2);
sys=ss(A,B,C,D);
t=0:100;
%% Adding Disturbances and Faults
amp=15;
E=amp*ones(5,2); %%disturbance matrix including uncertainties
```

```
disp('please input the fault time:');
t_fault=input('simulation start time=0s, end time=10s:');
disp('please input the fault type:');
fault_type=input('1=abrupt fault ,2= incipient fault,3=intermittent fault:');
%% Left Eigen Structure Assignment Method
rnk=rank(C*E);%%check
if (rnk<length(A))
   temp=C*E;
   W=null(temp');
   W=W';
   lhs=W*C;
   l=lhs';
   lambda=[-11.5397 -19.4274 -2.0692 -0.9755 -0.4240];
   P=-inv(lambda(length(A))*eye(length(A))-A')*C';%subspace span
   for j=2:length(A)
      ll=P(:,j)+P(:,j-1);%computing eigenvector from subspace
   end
   l(:,length(A))=ll;
   for i=1:length(A)
      P=-(inv(lambda(i)*eye(length(A))-A'))*C';
      w(:,i)=inv(P)*l(:,i);
   end
   %%check if li in span of P
    for i=1:length(A)
      P=-(inv(lambda(i)*eye(length(A))-A'))*C';
      proj_l(:,i)=P*w(:,i);
    end
    res=proj_l-l;
end
%% %% Observer Design
```

```
L=(w*inv(l))';
%% LQR
%for no fault conditions
Q=[50000000        0        0        0        0
   0    10000000        0        0        0
   0        0    10000000        0        0
   0        0        0    10000000        0
   0        0        0        0    10000000];
R=0.2*eye(2);
[K,ric,eig_new] = lqr(A,B,Q,R);
%for abrupt fault
Qab=[1000000        0        0        0        0
   0    1000000        0        0        0
   0        0    1000000        0        0
   0        0        0    1000000        0
   0        0        0        0    1000000];
Rab=0.2*eye(2);
[Kab,ricab,eig_new_ab] = lqr(A,B,Qab,Rab);
%for incipient fault
Qinc=[1e10        0        0        0        0
   0    1e10        0        0        0
   0        0   1e10        0        0
   0        0        0    1e10        0
   0        0        0        0    1e10];
Rinc=0.2*eye(2);
[Kinc,ric_inc,eig_new_inc] = lqr(A,B,Qinc,Rinc);
%for intermittent fault
Qint=[1e8        0        0        0        0
   0    1e8        0        0        0
   0        0    1e8        0        0
```

```
  0        0        0    1e8        0
  0        0        0        0    1e8];
Rint=0.2*eye(2);
[Kint,ricint,eig_new_int] = lqr(A,B,Qint,Rint);
%% FTC
  model = 'thesis_lqg';
  load_system(model)
  sim(model)
%% Plots
figure;
plot(r_fault,'linewidth',1.2);
xlabel('Time(s)');
ylabel('Residual Signal,r(t)');
title('');
figure;
plot(yhat_out,'linewidth',1.2);
xlabel('Time(s)');
ylabel('LQG Output,y(t)');
title('');
magnify;
%
```

The above MATLAB script loads data of all the required parameters to a Simulink model which then applies the algorithm proposed in this thesis for FTC.

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