CHAPTER 1

Introduction

Flight control actuation system forms a mission critical subsystem in the avionics system of any aerospace vehicle. Control actuators are widely used in the aerospace industry in the flight control system of aircrafts, missiles and launch vehicles. Faults in the actuation system of the vehicle can endanger operational safety, causing risk to human life and prohibiting accomplishment of the intended mission. Expeditious diagnosis and prognosis of faults in such mission critical systems is thus essential to initiate proactive steps like mission salvage to prevent loss of vehicle in presence of impending failures. Further, in case of aircrafts it allows condition based maintenance scheduling which is more reliable and cost effective than scheduled maintenance or reactive maintenance.

Aerospace systems in which faults could result in a catastrophic failure are designed to be fault tolerant. This is usually achieved through hardware redundancy. To enable normal operation to continue in presence of a fault, critical avionics hardware, such as sensors and computers, are repeated in triplex or quadruplex [1]-[3]. Multiple elements are usually distributed spatially around the system, wherever possible, to provide protection against localized damage. Such schemes operate by comparing outputs from these multiple hardware elements by majority voting so that software/hardware faults may be detected and isolated. The major problems encountered with hardware redundancy leading to investigations into other forms of fault detection, are the extra mass and the space required to accommodate these, which could be used for useful payload. Further, it is also recognized that since identical redundant components like sensors tend to have similar life expectancies, it is likely that when one of a set of sensors malfunctions the others may soon become faulty also [4].
An alternative to hardware redundancy that permits deep diagnosis of faults is the analytical redundancy technique. This technique is based upon the idea that three or more dissimilar sensors measuring different variables, and therefore producing entirely different signals can be used to detect a fault in one of the set. The rationale for this idea is that even though the sensors are dissimilar, they are all driven by the same dynamic states of the system and are therefore functionally related [4]. Thus, in analytical redundancy based FDI, the inherent redundancy contained in the static and dynamic relationships between the system inputs and measured outputs is exploited for fault diagnosis. The underlying principle of analytical redundancy based fault diagnosis is that systems provide advance warning of failure through symptomatic performance degradation. By detecting and identifying these symptoms early in their onset, maintenance may be carried out before system safety and availability are compromised. Use of analytical redundancy based FDI techniques offer advantages in cost, mass, power consumption and reliability over conventional FDI schemes.

The analytical redundancy based FDI schemes are basically signal processing techniques employing state estimation, parameter estimation, adaptive filtering, variable threshold logic, statistical decision theory, and various combinational and logical operations, all of which can be performed in a high speed digital computer. Normally, both the input signals to the actuators and the output signals from the sensors are used to estimate the states and parameters required for analytical redundancy.

This thesis has attempted analytical redundancy based schemes for the diagnosis of faults in a flight control actuation system.

1.1 Background and Motivation

The initial impetus for undertaking this research work came during the design of a reliable control actuation system for a satellite launch vehicle. The schematic of a linear control actuator used for gimballing a rocket engine is shown in Figure 1.
In a liquid rocket engine the fuel and oxidizer are kept in separate tanks and they are then fed into the combustion chamber at a specified flow rate. The high temperature and high pressure combustion products produced in the chamber expand through a nozzle with high velocity imparting a momentum in the opposite direction to the vehicle. To steer the vehicle as per the required trajectory and to make required corrections the thrust vector of the vehicle is deflected with respect to the vehicle axis. For this purpose, the engine is mounted on a gimbal mount which permits it to be swiveled in two orthogonal planes. Normally two actuators, either electromechanical or electrohydraulic are mounted in orthogonal planes. The actuators are controlled by the control electronics based on the commands from the guidance and control system of the vehicle.
In flight control system for launch vehicles, even though the navigation sensors and flight computers are made redundant, the control actuator used for actuating the rocket engine or nozzle to generate control moment is kept single. The required reliability in such control system is generally achieved using good quality parts, component derating, component screening and assembly procedures and through extensive testing.

The avionics components used in the actuation systems such as LVDT’s, Power amplifiers, Processors, Resistors, Capacitors, Motor windings, etc. have a finite failure rate. However in most of the actuation systems for launch vehicles only single elements like sensor, motor coil, etc. is used that may lead to a single point failure in the system. Though such actuators meet the reliability requirement for short duration satellite launching missions, they may not have the required reliability for extended time missions like lunar missions or manned missions. Further, the sources of single point failure in such systems are to be avoided as random failures in such sources can be catastrophic. Hence for increasing the reliability of actuation system and making it fault tolerant, it is necessary to incorporate redundancy, especially for the weak elements of the control actuation system.

This redundancy can be introduced at various levels ie. component, subsystem, etc. depending upon probability of failure and reliability goals. A straightforward solution to the above mentioned problem would be to add one more redundant chain of components in controllers, sensors, motor or servo valve coils, etc. This dual redundant system itself can be configured in many different ways depending upon how the sensors, windings of the motor or servo valve are utilized [5]. For the purpose of investigation an Active/Standby configuration as shown in Figure 2 is considered in this thesis mainly due to the simplicity of the configuration.

This configuration includes two independent processing channels operated in an active/standby arrangement. In normal fault free operation, channel 1 is connected to one of the windings of the motor. The sensor set 1 consisting of feedback sensors is also connected to channel 1. In case of a failure in channel 1 the entire control is
switched to channel 2 including the second motor winding and sensor set 2. Simple On/Off switches can be used to engage the active or standby channel. The major problem in such dual redundant schemes is the determination of the occurrence of a fault in one of the channels so as to switch over to the standby chain. If this fault can be detected unambiguously, then the dual chain configuration would be preferred to higher degree of redundancy which is generally used for fault detection. This has been the major motivation for this research work focusing on fault detection and isolation in a dual chain control actuation system.

**Figure 2: Active/Standby - Dual chain configuration**

At this juncture, it is appropriate to mention the major drawbacks of TMR/Quadruplex chain systems which are generally used for fault detection by incorporating additional hardware chains in the system. While TMR/Quadruplex systems increase the reliability of actuation systems and make the system free from single point failures, they suffer from the following disadvantages.

Increase in
- Weight
- Power Consumption
- Cost
- Space
- Circuit Complexity
- Design and Testing time.

Hence, this research focus on fault detection in dual chain systems through the "Analytical Redundancy FDI" approach wherein a mathematical model is used to identify the faulty chain in a dual redundant system configuration.

Survey of analytical redundancy based FDI techniques indicate that in spite of significant developments in this field over the last four decades, there has not been wide spread use of this technique in practical aerospace flight control systems. The main reason for this can be attributed to the lack of a robust FDI scheme suitable for real time implementation onboard, that would work in presence of significant nonlinearity, sensor noise, disturbances and plant parameter variations in the system under realistic control input conditions. The saturation nonlinearity that exists in most of the practical control actuators needs special mention as many of the FDI techniques developed earlier do not perform satisfactorily in presence of hard nonlinearities like saturation. This research aims to fill this gap existing in currently developed FDI techniques and aims at the development of a robust fault detection and isolation scheme that can be put to use in practical launch vehicle control systems in presence of saturation nonlinearity.

1.2 Problem Definition

A fault is defined as an unpermitted deviation of at least one characteristic property of the system from the acceptable/usual/standard condition [6]. The fault detection problem in a control system consists of making a binary decision, whether a fault exists in the system or not. The fault isolation task on the other hand consists of determining the source of the failure, ie. which particular sensor or component in the control actuator has failed. The fault detection problem is more important than the isolation problem in satellite launch vehicles as delays in detecting the fault in certain phases of the mission can lead to catastrophic events like vehicle becoming uncontrollable. The maximum delay that can be tolerated from the onset of a fault to the time of detection of the fault must not exceed a few hundred milliseconds in case of most launch vehicle missions.
Type of control actuator considered in this problem

As mentioned in the previous section, the main motivation for undertaking this research is to develop an analytical redundancy based technique for detecting faults in a dual chain control actuation system operating in active/standby mode. The control actuators used in launch vehicle control systems can be broadly classified into two types depending on the technology used, Electrohydraulic or Electromechanical actuators. In an electrohydraulic control actuator, hydraulic fluid is the primary source that generates the control force by varying the pressure and the flow of the hydraulic fluid to the actuator. Electromechanical control actuators, on the other hand make use of electric motors, either brushed or brushless, for generating the control force.

Electrohydraulic actuators are used extensively in the aerospace industry, especially in aircraft/launch vehicle systems. Electrohydraulic actuators generally have higher power to weight ratio compared to electromechanical actuators making them attractive in the design for high power applications. In general, systems requiring bandwidth greater than about 20 Hz or control power greater than about 15 kW are better suited for electrohydraulic actuation systems [7]. The main disadvantage of electrohydraulic actuators is that the hydraulic fluid must be continuously filtered and cleaned. Presence of contaminant can result in the failure of the system. Further, electrohydraulic actuators when used for low power actuation applications may result in larger weight compared to electromechanical actuators. The recent development of high energy magnets like Samarium-Cobalt and Neodymium (alloy of neodymium, iron and boron) have resulted in weight optimized design of high power electric motors for aerospace applications [8]. The electric actuator offers the following advantages.

- Increased safety due to elimination of inflammable hydraulic fluids.
- Easier and reduced maintenance due to elimination of hydraulic leaks and better diagnosability.
- Reduced weight and complexity of power transmission paths.
- Better energy efficiency of electrically powered systems.
In view of the existing trend in the aerospace industry to go in for electromechanical actuators, this thesis addresses the fault detection and diagnosis problem for an electromechanical flight control actuator. The block diagram of a typical electromechanical flight control actuation system used in launch vehicles is shown in Figure 3. A typical linear electromechanical actuator used for gimballing a rocket engine (as shown in Figure 1) is considered for the research problem in this thesis.

**Figure 3: Block diagram of a flight control actuation system**

The major components in an electromechanical control actuation system are the actuator, feedback sensors, controller, servo amplifier and the load. The actuator consists mainly of the DC torque motor and the ball screw mechanism. The feedback sensors used by the actuator consists of position sensor like Linear Variable Differential Transformer (LVDT), shaft velocity sensor like tachogenerator and motor current sensor. The load dynamics in the actuation system considered is predominantly dominated by the inertia of the ball screw and engine nozzle.

Even though we are addressing a dual chain actuator configuration, the modeling of the actuator is done for a single chain system as only one set of sensors and motor coil is functionally active at a time.
Robustness of analytical redundancy based FDI schemes to parameter uncertainties, unmodelled non-linearities/dynamics, external disturbances and sensor noise.

The robustness of an FDI scheme is the degree to which its performance is unaffected by perturbations in the operating parameters which turn out to be different from what they were assumed to be in the design of the FDI scheme [4]. Therefore robustness must be measured with respect to the variables associated with those conditions. Analytical redundancy based fault detection essentially relies on a mathematical model of the system. Thus one of the main prerequisite in implementing analytical redundancy based FDI is the availability of a reasonably good mathematical model of the system. A major problem in the field of robustness in FDI schemes arises from the uncertainties in the physical parameters at the operating point. In most plants, even those that are modeled accurately as linear and time invariant (the simplest class of dynamic system), some physical parameter values are known only approximately. Hence the FDI scheme is often designed using only nominal values for the uncertain parameters and some accommodating mechanism is used to compensate for this uncertainty. This may cause the FDI scheme to produce false alarms or in case of accommodating mechanisms may fail to detect a fault. This robustness problem with respect to parameter uncertainties had to be taken care of during the design of the FDI scheme for control actuator.

All dynamic plants are nonlinear, whilst many behave almost linearly provided it operates in a narrow range around a nominal operating condition. An FDI scheme based on linear models might be quite satisfactory for these conditions. However, for large changes around the operating point, the nonlinearities of the plant produce signals which are not accurately captured by linear models used for FDI scheme, and these may then be interpreted as faults thus resulting in lack of robustness in the FDI scheme with respect to unmodelled nonlinearities or uncertain dynamics.

Many of the analytical redundancy approaches for Fault Detection and Isolation (FDI), such as state estimation using observers or Kalman filters, parity space &
parameter estimation techniques are derived mainly for linear systems [9]. Practical systems such as flight control actuation systems have significant nonlinearity such as friction, power amplifier saturation, etc. If the nonlinearities of the system are not considered in the model used for FDI, these nonlinearities which are not modeled accurately by the FDI scheme produce signals that may be interpreted as faults. Many of the earlier developed FDI schemes for control actuators have ignored the effects of such nonlinearities. Here, saturation nonlinearity needs special mention as this is a significant nonlinearity in practical flight control actuator. In fact one of the major reasons for the lack of practical implementation of FDI scheme in flight actuators is the inability of many developed FDI schemes to handle saturation nonlinearity. This research work aims to bridge this gap existing in FDI schemes for control actuators and will attempt to develop a robust FDI scheme capable of handling hard system nonlinearities like saturation and friction existing in flight control actuators.

Dynamic plants are always subjected to inputs other than those intended by the system designer. These inputs, called disturbances, are usually random fluctuations originating in the environment, such as fluctuations in the wind. Furthermore, the sensors used as feedback elements in the control actuator usually have electronic noise superimposed on their signals. This noise is also random, but it originates from a different source and is normally uncorrelated with the disturbances. The effects of these disturbances and sensor noise are to produce false alarms by the FDI scheme. Hence the robustness issues with respect to external disturbances and sensor noise has to be addressed in addition to parameter uncertainties and unmodelled nonlinearities. This research work attempts to address the above issues.

Many of the earlier works in actuator FDI have used simplified models of the actuator for FDI purpose. Important contributing factors to overall system response in presence of mounting structure stiffness of actuator and load dynamics were ignored. Further, effects of inner loops like current loops used in the power amplifier stage of control electronics of actuators were also not considered. Presence of closed loops can very often obscure the detection of faults in the system. The work in this
thesis aims to overcome some of the limitations of previously developed FDI schemes for flight control actuators. For this purpose, the detailed model of the flight control actuator, which considers system nonlinearities, mounting structure stiffness, load dynamics, compensators, power amplifier, current loop and sensor noise is used for deriving the FDI scheme.

(iii) Type of faults to be detected and isolated – Sensor faults and actuator faults

The type of faults that can occur in the flight control actuation system shown in Figure 3 can broadly be classified into three types as given below

(i) Sensor faults – ie. Faults occurring in the feedback sensors like LVDT, tachogenerator or current sensor.

(ii) Actuator faults – ie. Faults occurring in the actuator components like DC motor and associated mechanical components

(iii) Controller faults – ie. Faults occurring in the controller or power amplifiers.

The two weak elements sensitive to failures in the electromechanical actuator are the dynamic active elements; mainly the electric motor and the feedback sensors. In case of launch vehicle missions, the actuator is to be designed in the most optimal way because of weight constraints. Quite often, actuators used in launch vehicle flight control system are designed for peak rating for a limited duration mission for minimizing the size and weight of the system. This requires continuous health monitoring of the motor used in the control actuators of launch vehicles. Detection of motor faults is required for taking precautionary steps to prevent loss of vehicle while deep diagnosis of motor faults may be required for taking maintenance actions as necessary for actuators in aircrafts.

Feedback sensors like LVDT’s, Tachogenerator and optical shaft encoders are dynamic elements continuously undergoing mechanical movements. However, the
final mechanical attachment of LVDT’s to the actuator is prone to single point failures which cannot be detected by conventional monitoring methods. Current sensors also are prone to failures due to overloading. Hence, it is essential to provide monitoring of sensors for detecting possible occurrence of faults. As in the case of motors, detection of sensor faults is essential to initiate proactive steps for mission salvage. Feasibility for sensor reconfiguration in presence of faults is another desirable feature of the FDI scheme.

The above discussion highlights the need for developing fault detection and isolation techniques that addresses sensor as well as actuator faults independently. This research work therefore focuses on the development of FDI techniques that can be applied independently for detecting sensor as well as DC motor failures in the actuator. It is proposed to develop FDI scheme for isolation of the faulty sensor in case of sensor failures and in-depth fault diagnosis in the case of actuator failures of the DC motor.

The present day controllers are mostly implemented in digital processor where the schemes for detecting its own fault through self checking is well established. FDI schemes for detecting the failure of power amplifiers in electromechanical actuators by current monitoring and other methods have also been developed and are currently in use. Hence, controller failures are not addressed separately in this work. Nevertheless, as the analytical redundancy based FDI scheme does end to end monitoring of the system from control input to final actuator position output, such faults also will get detected by the scheme.

(iv) Requirement of a unified scheme for detecting both types of faults

The previous section has highlighted the requirement of developing independent FDI schemes capable of detecting and isolating sensor or actuator motor faults. Another requirement which is particularly useful in launch vehicle missions is the development of a unified FDI scheme capable of detecting sensor as well as actuator motor failure. While there have been a number of FDI approaches that has addressed either the sensor or the actuator faults separately, there still exists a gap in the
development of a unified FDI scheme, that addresses all the robustness issues mentioned earlier. This research aims to fill the gap by developing a unified FDI scheme that works in presence of hard system nonlinearities like saturation and friction and is robust to external disturbances, parameter variations and sensor noise.

The desirable characteristics of the FDI schemes that is to be developed are as follows.

- It should detect abrupt faults ie. step like faults as well as incipient faults eg. bias or drift in the feedback sensors.
- It should not give false alarms.
- There should not be any missed faults.
- The FDI scheme should be prompt in declaring the fault.
- The scheme should be robust in presence of measurement noise.
- The scheme should be robust to parameter variations.
- The scheme should be robust to external disturbances.
- The scheme should work in presence of nonlinearities specifically friction and saturation nonlinearity.
- It should be amenable for easy implementation in an on-board computer.
- The fault detection and isolation process should be carried out in such a way that it does not obstruct or slow down the operation of the actuation system.
- Feasibility for sensor reconfiguration is a desirable feature though not essential.
- The scheme should detect sensor faults as well as actuator faults.
- The execution time of the FDI algorithm shall be less than the actuator control loop execution time (5 milliseconds for thesis example).

Any FDI scheme that is developed is useful only if it is feasible to implement it in real time in an on-board flight computer. Hence, this research work will make an assessment of the execution time of the developed FDI scheme for implementing it in a Digital Signal Processor (DSP) based flight computer. Based on the developed FDI schemes, a minimal fault tolerant dual redundant control actuation system
configuration is proposed that if implemented in launch vehicle flight control actuation systems will significantly improve the reliability and availability of the control actuation system.

1.3 Objectives of the Research Study

Based on the above problem definition the following five main objectives are outlined for this research study.

(i) Develop an FDI scheme capable of detecting sensor faults in the control actuation system using the analytical redundancy between the measured variables. Isolating the faulty sensor and system reconfiguration for continued operation is a secondary objective of the research work.

(ii) Develop an FDI scheme capable of detecting actuator faults, mainly faults occurring in the DC motor of the actuator. Isolating the type of actuator fault is a secondary objective of the research work.

(iii) Develop a unified FDI scheme that is capable of detecting sensor faults as well as actuator faults in presence of hard saturation and friction nonlinearity. The scheme should be robust to sensor noise, plant parameter variations and external disturbances.

(iv) Carry out the development of the software for implementing the FDI scheme in a DSP processor based flight computer. Assessment of the execution time for executing the FDI scheme in the DSP processor to be carried out.

(v) Propose a minimal fault tolerant dual redundant actuator configuration based on above developed schemes that can continue with the system operation after one sensor or motor coil failure.
1.4 Approach

The basic building blocks of FDI in systems are the methods for detecting faults and subsequently diagnosing their causes. There are a number of techniques existing in the literature for the detection and diagnosis of faults in dynamic processes. The wide ranging array of methodologies and alternatives often leave the user confused and wondering about the suitability of a method for his or her application. The applicability of these methods depends on the process under consideration and the type of faults that are to be identified. Each of the methods has its advantages and disadvantages. Depending on the requirement, the advantages of each of these methods can be combined properly for realizing the desired goal. Survey of fault diagnosis methods in control actuation system indicated that there are different techniques existing currently as indicated in Figure 4.

Figure 4: Classification of fault diagnosis methods

These techniques for fault diagnosis can be broadly classified into three general categories [10]-[13].

(i) Quantitative model based methods
(ii) Qualitative model based methods

(iii) Process history based methods

Literature survey of FDI techniques indicates that methods based on process history are suitable when no other methods exist [13]. Process history based methods are applied for problems for which theoretical models of system behavior are inadequate to explain observed performance. Most of the fault diagnostic in process industries are based on process history approaches. A large amount of training data is needed, representing both normal and faulty operation. Hence, such methods are used when training data are plentiful and inexpensive to create. A disadvantage of this technique is that in most cases the models cannot be extrapolated beyond the range of the training data.

Approaches based on qualitative models, on the other hand are well suited for data rich environments and non-critical processes. Although these methods are easy to develop, it is difficult to find a complete set of rules, especially when the system is complex. These models to a large extent, depend on the expertise and knowledge of the developer. Generation of spurious solutions is reported as major disadvantage while reasoning with qualitative models [11]. Many of the academic demonstrations of these models have been for very simplistic systems and implementing them for industrial systems is beset with problems related to computational complexity and generation of spurious solutions.

Most of the work in aerospace and electrical engineering literature has concentrated on quantitative model based diagnostic systems [10]. They provide most accurate estimation of output when they are well formulated. Further, they also have an advantage in modeling the transient behavior of the systems more precisely than any other modeling technique. The main disadvantage of quantitative model based approach is that they are computationally intensive. Since DC motor based electromechanical actuator is considered here, it is possible to obtain a reasonably good analytical model of the system. Hence it is proposed to pursue the quantitative model based approach for the control actuator FDI problem. The quantitative model
based approach uses either the observer, Kalman filter, parameter estimation or parity space based techniques for actuator FDI.

Isermann has provided a good survey on the trends in the application of model based fault detection and diagnosis of technical processes based on application oriented publications in this field over a period of five years [6]. This survey indicates that for fault detection purpose, the application of observer/Kalman filter and parameter estimation methods depends on the type of fault. They are used in nearly 70% of all applications considered. Neural networks, parity space and combined methods are applied less often. More than 50% of sensor faults are detected using observer/Kalman filter based methods. For the detection of actuator faults also, observer/Kalman filter based methods are mostly used followed by parameter estimation and neural network methods.

Considering the above trend, it is proposed to pursue the observer/Kalman filter based approach for sensor and actuator fault detection in the system under consideration. The main advantage of the Kalman filter is that it is formulated in a stochastic framework. In practical control systems, faults are random in nature. They may occur at random instants of time, have unknown size, and can happen at system component. Moreover, control systems in practice are subject to measurement noises and disturbances from the surroundings. In addition, the majority of FDI algorithms rely on statistical hypotheses tests. This necessitates the system to be modeled as stochastic system as in a Kalman filter. Due to the above advantages it is expected that the Kalman Filter based approach will be suitable for the FDI problem in flight control actuation systems. However, use of the linear Kalman filter for actuator FDI can pose problems, especially in presence of significant nonlinearities in the system like saturation and friction. Hence extensions of Kalman filter estimator, like Extended Kalman Filter (EKF) and Unscented Kalman Filter (UKF) will have to be explored to see the suitability of these techniques for actuator FDI.
The following are the assumptions made in this research work

- The system has a defined state, that is, the dynamics of the system can be modeled with ordinary differential equations.
- The system is nondeterministic, i.e. noise affects its operation.
- Sensor readings are the primary source of information of the state of the system. These readings may contain noise, which is modeled as Gaussian noise.
- Faults appear one at a time.
- The moment of inertia of the system does not change with time.

1.5 Outline of Thesis

The organization of this thesis is as follows. Chapter 1 describes the background and motivation for undertaking this research work. It briefly describes the problem to be solved, objectives of the research, the planned approach and assumptions made in this research. Chapter 2 presents the literature survey of fault detection and isolation in dynamic systems. An overview of the different fault types that occur in systems, the common FDI methods, performance measures and comparison of different FDI techniques are presented in this chapter. Chapter 3 describes the actuation system under consideration and its mathematical modeling. Chapter 4 presents the detection and isolation of sensor faults in the system using techniques based on the Luenberger observer and linear Kalman filter. Reconfiguration of the system in presence of failure of the feedback position sensor is also presented. Chapter 5 addresses the detection and isolation of actuator faults in the control actuation system by configuring the Extended Kalman Filter (EKF) as a simultaneous state and parameter estimator. Application of fuzzy inference for effective diagnosis of actuator faults is also demonstrated in this section. Chapter 6 presents a unified approach for diagnosis of sensor and process faults using the additive form of the Unscented Kalman Filter (UKF-A). Fault diagnosis in presence of saturation nonlinearity is specifically addressed in this chapter. Chapter 7 presents the assessment of execution time of the developed FDI scheme for implementation in a DSP processor. A minimal fault
tolerant dual redundant actuator configuration is proposed in this chapter as an outcome of this research work.

Chapter 8 describes the conclusions and main contributions of this research work. Finally, the scope for future research is also presented.