Chapter 1

Introduction

1.0 Faults and their Classification

A fault in a system is an undesirable physical change, which causes degradation of performance. Faults may result from sudden or slow malfunction of components and errors in design or specification. Failure on the other hand is the permanent interruption of a system to perform a required function under specified operating condition. Generally research in fault tolerant control begins by assuming a specified model of the system as a nominal model and any major deviation of the system behavior from the nominal model is considered as a fault.

Faults are classified as permanent, transient or intermittent depending on the duration of their existence. Permanent faults usually arise from damage in components; say structural parts (e.g., breakage of control surface in aircrafts, engine failures in vehicles etc.). Transient faults have their origin in disturbances and exist only for a finite period of time. In the case of intermittent faults, the system or plant switches between faulty and fault free states. This is also called a malfunction. A precise definition of malfunction is intermittent irregularity to perform desired function. Example of this type of faults is intermittent loss of contact of power supply of the actuating motor, thus making the actuator intermittently stagnant. Other reasons for intermittent faults are ageing of components, abnormal input condition or improper operating environment. These types of faults occur quite frequently and are difficult to detect. But left undetected, these may produce instability in system operation.

Some faults grow very slowly and in the initial stage, their signatures are not prominent. In this stage the faults are called incipient fault. They are difficult to detect, but if no remedy is taken they can later develop into large faults.

In practical situations when we consider a complete mission during any satellite launching or warhead deployment, there may be more than one fault occurring at different time instants. This group of faults is defined as serial faults. If a component recovers from faulty condition without any repair or maintenance we may call it a fault recovery.

Faults may occur in sensors, actuators and in the main operating parts of a plant. When the main operating part of a plant fails, it is called a process fault. Process faults, in general, produce catastrophic effects like complete plant shutdown. However there may be less severe faults or malfunctions in sensors or actuators which may be tolerable. Malfunctioning of any measuring instrument in a system (Gyroscope, pressure gauge, temperature sensor) is known as sensor fault. Sensor faults exhibit themselves as biases or corruption in output. Also in some faults, sensor output can remain constant, even though the physical quantity it is measuring is varying with time. Actuating part of a system (Hydraulic, pneumatic, electric) may also fail and this is called an actuator fault. Faults in actuators cause loss of effectiveness which may be either partial or complete. In some faulty conditions actuators stop moving and remain stagnant at a constant position. This is called stuck fault of an actuator.

1.1 Fault Detection, Identification (FDI) and Reconfiguration

Fault detection is the task of determination of faults present in the system. Determining the time, location, and the kind of fault is called fault isolation. Whereas determining the size and time variant bevior of the fault is called fault identification. Generally these steps are followed sequentially in fault detection and identification process. Fault tolerant control is implemented using the information available from these three steps.

Fault tolerance in any system can be achieved either by passive or active techniques [10]. Passive fault tolerance is achieved by designing the control system in a robust manner so that the designed control strategy maintains performance in spite of occurrence of faults. The approach is basically robust-control oriented and the design methodology takes care of the uncertain perturbation of parameters. On the other hand, active fault tolerance involves detection of the onset of a fault, identification of its location and finally reconfiguration of the control system to mask the effect.

Active fault tolerance is basically a two-stage approach [10]. In the first stage, the fault is detected and isolated. In stage two, the control system is reconfigured to maintain the desired performance. The general methodology of fault detection is schematically shown in Figure 1.1. The fault detection algorithm accepts input and output of the plant. Then corresponding to a given input signal to the plant, the algorithm predicts the output. The predicted output is compared with the actual plant output to generate the residual. Magnitude of the residual is used to detect the fault. Some properties of the residuals are used for fault isolation.

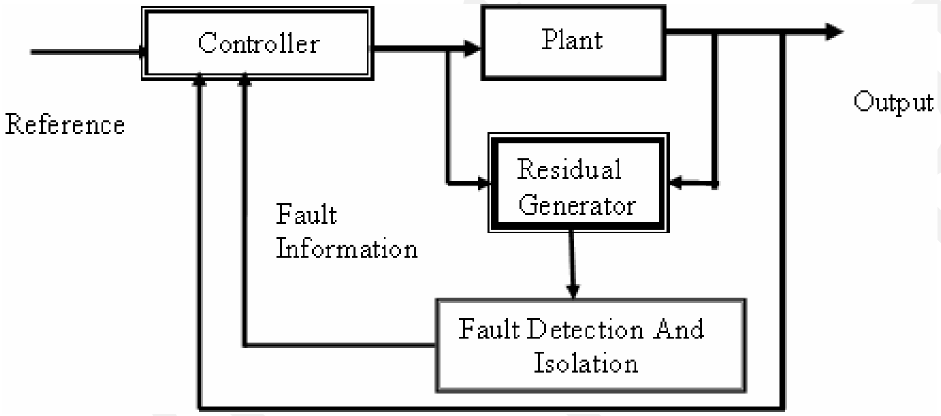

Figure 1.1: A general Fault Detection, Isolation and Reconfiguration scheme

The fault information is used by a reconfiguration method to reconfigure the controller for performance restoration.

The body of knowledge on fault detection is huge. It ranges from simple threshold detection to multiple observer-based techniques [61]. The integral part of detection comprises a hypothesis testing which involves probabilistic techniques like the likelihood ratio testing. Fault detection methods fall broadly into following classes.

(a) Plant Model based approach: This class comprises the model-based methods where the plant model is assumed to be known. The plant outputs are compared with model-generated outputs. Any deviation between the two depicts a fault. This deviation, known as a residual, is tested against a threshold which may be decided and fixed at the design level or may be changed dynamically depending on change in the reference command input.

(b) Signal model based approach: In this approach signals measured by sensors are analyzed using mathematical functions and signal processing techniques. These include correlation function, Fourier analysis, Wavelet analysis etc. Features extracted from signals are compared with known features of the fault to detect a fault. An example is the spectrum of the vibration signal, which is used to detect fault in gear failure in a mechanical system.

(c) Multivariate Statistical Techniques: Statistical analysis is carried out on multiple parameters. Joint probability distribution and interrelation between the parameters is analyzed in a statistical way to determine the feature of fault. Empirical models derived from statistical techniques are also used for fault detection. One example of multivariate statistical method is the principal component analysis, where using a transformation, key parameters of variation are determined.

(d) Knowledge based approach: This class of fault detection algorithms depends on the knowledge-based approach in which Artificial Neural Networks (ANN) and Fuzzy logic are used for fault detection.

Fault isolation is the task of locating the fault. This is accomplished by testing some special features of the residuals against their predefined nature. Suppose for each possible fault we define a residual. Then building up of a residual indicates that the corresponding fault has occurred. If the residual is a vector, its directional properties may contain information regarding the component which has failed [46]. Voting scheme is very popular for detection of sensor faults. If three identical sensors measure a single quantity then deviation of output of one sensor from that of the other two depicts failure of the particular sensor. Recently, multiple-model based methods are becoming more and more popular. A performance index is defined for each model which is based on the difference between model predicted output and actual output of the system. The model for which the performance index is minimum represents the plant status more closely.

Reconfiguration is the methodology of changing the control or measurement strategy so as to maintain the performance as close as possible to the fault free system

[10]. In most cases automatic reconfiguration is necessary in aircrafts and aerospace vehicles as the upper time bound for reaction to faults is very small. Unmanned vehicles have no provision for manual reconfiguration.

Reliability is the ability of a component, process or a system to perform a required function correctly under stated condition within a given scope, during a given period of time. Thus reliability plays a major role in the availability and safety of the system. Reliability can be affected by faults and malfunctions. Two other related terms are maintainability and availability. Maintenance is an action taken to retain a system in, or return a system at its desired operating condition in the presence of degradation and fault. Availability is the probability of a system to perform or function correctly at any given time. All the three terms, reliability, availability and maintainability plays key roles in the over all life cycle of a product. A fault management scheme can improve in all the three by suitable planning of maintenance.

Reliability is very closely related to fault tolerance because fault masking enhances it. Reliability is highly dependent on redundancy in the system regarding actuation and measurement mechanism [10]. Hardware redundancies in the system can considerably increase reliability. The voting scheme in sensor fault detection is based on hardware redundancy. Similar redundancy can exist in actuators. For example, a tracking antenna may employ two motors per axis, but positioning can be accomplished by a single motor per axis. In this context the types of redundancies are described below:

(a) Static Redundancy: In this case all of the redundant modules operate in parallel and a voting scheme is employed to choose the functional ones. Let us assume that three sensors are measuring the same quantity. If one of them has a reading far away than the other two, then it is assumed that the former is faulty.

(b) Dynamic redundancy: In case of dynamic redundancy a fault detection scheme determines the healthy module as it is switched to the system by means of a selection switch. When all the modules are in powered on condition it is called hot standby, otherwise it is called cold standby.

Hardware redundancy plays an important role in designing a fault tolerant control scheme. If we have sufficient hardware redundancy then fault tolerance is easily achieved and cost of implementing a fault tolerant control scheme is reduced. But addition of extra hardware involves increase in weight and cost. Weight is considered as a drawback in any airborne vehicle. Cost is a prime criterion that should be reduced in any commercial product.

Interestingly, most systems have inherent redundancies in actuation and measurement mechanism [10]. Exploiting this, fault tolerance can be employed without any extra hardware other than those used during the system configuration. The concept depends on controllability and observability features of the faulty system. If the system is controllable after an actuator or process fault, a new controller may be designed which will retain the system performance utilizing the healthy system components. In the case of sensor faults, for an observable system, the faulty sensor outputs can be reconstructed using the estimated states of the system. Reconfiguration may be employed either by controller switching or by online controller design. For anticipated faults, previously designed controllers' parameters are stored in a control computer's memory. After a fault is detected and isolated the controller corresponding to that fault is switched. Real time redesign is a relatively new technique that has yet not been employed widely. Some special cases of redesign have been applied in spacecrafts, ship propulsion system, and process control.

Finally it is worth mentioning that if the objective of the plant cannot be fulfilled under any faulty condition the objective itself may have to be modified to be less demanding. If the plant cannot track the reference under faulty condition then at least it should be stabilized to prevent further damage. This serves as a typical example of objective reduction.

Some authors use a general term 'restructurable control' for controller reconfiguration [80]. Restructurable control is applicable for systems where controlling capability can be obtained fully or partially as that of the healthy system from a faulty one using the healthy control effectors. Controller is designed on-line without the help of any human intervention. There should be a method to determine the effectiveness of the current control mode. A technique should be there to identify the faulty actuators and to characterize the remaining actuators. Restructurable control uses a routine to design the controller on-line for the faulty system [80]. These tasks are performed by an expert system. The expert system is composed of three components. A knowledge base keeps record of the description of the system. For linear time invariant system this may be the system matrices in state space description at any time instant. A rule base consists of the rules used to design the control system. This may also contain the definition of controllability and observability. Naturally, the rule base contains expressions to be evaluated. The inference engine works with the knowledge base and rule base to evaluate certain rules [80]. Investigation in the field of fault tolerant control by combining FDI techniques with supervisory control in a ship propulsion system has been attempted by Zamanabadi and Blanke [134].

1.2 Performance Criteria of a Fault Tolerant Control System

A well-designed Fault Tolerant Control (FTC) system should be capable of detecting and isolating a fault promptly. It should be able to determine the severity of the fault. The reconfiguration method must take necessary action to mask the effect of fault. Following criteria are necessary for Fault Tolerant Control [46, 52].

(1) Promptness: The detection methodology should be able to detect the fault within a short period, less than any dynamic time constant of the faulty system. This is very important for aerospace applications since delay may cause severe instability resulting in loss of vehicle, human life and mission failure.

(2) Sensitivity: Sensitivity of a FTC system is defined as its capability to detect faults of small size. The detection methodology should be capable of detecting intermittent and incipient faults. Understandably, the capability of detection of serial faults and fault recovery with low rate of missed faults constitutes an important criterion for any FTC.

(3) Low False Alarm: False Alarm is particularly dangerous when reconfiguration is done automatically. False Alarm in automatic reconfiguration system causes incorrect controller switching. This may cause unstable system operation. Therefore rate of false alarm should be low enough.

(4) Robustness: Modeling errors and disturbances are major causes for erroneous fault detection. Robustness is the property by virtue of which FTC system remains invariant to disturbances and modeling errors. Sensitivity and robustness are two opponents in a game. A very robust FTC loses sensitivity and on the other hand a very sensitive FTC is susceptible to disturbances and modeling errors.

The presence of disturbance and modeling errors poses real challenge in the design of a fault diagnosis system, since both behave in a manner similar to faults. Disturbances are external inputs, the effect of which a plant should suppress and fault diagnosis algorithm should not detect them as faults. Disturbances affect the plant as additive faults and can be decoupled perfectly only if the number of disturbance inputs is less than the number of faults and the way they affect the plant is known. Otherwise, an approximate decoupling is possible by minimizing the effect of disturbance with respect to the effect of the fault. Modeling error acts as parametric faults on the system. The effect of modeling error can be considered similar to the effect of disturbances. Thus the effect of modeling errors can be minimized. A long-term study of the system behavior provides the necessary clue to decouple modeling error from fault.

(5) Bumpless transfer: This is an important criterion for reconfiguration. During controller switching there should be minimum overshoot. The integral windup problem should be taken into consideration. It should be ensured that actuator signals just after switchover become equal to the actuator signals just before switchover.

The characteristics of FTC system should be chosen after analyzing requirements of the plant. For a process control system where dynamics is slow, decision can be taken after collection of enough data from the plant. This may incorporate a delay in the detection method, but it reduces the chances of false alarm. In a thermodynamic system, say Variable Air Volume Air Conditioning System, when temperature change occurs slowly we have sufficient time to identify the fault and reconfigure the controller to accommodate it. On the contrary, in aerospace system time for reaction is small. So FTC should be fast enough, but at the same time it should be robust against False Alarms.

1.3 Analytical Redundancy based methods in Fault Diagnosis

The research work presented in this thesis will be based on the use of analytical redundancy techniques. The output or the states of the plant are computed from the model of the plant using the inputs of the actual plant. Then the outputs predicted by models or states are compared with the actual plant outputs or states. The results of this comparison are the residuals which bear the signature of the fault. Analytical redundancy based techniques can be classified broadly into four different categories [46].

(1) Parameter Estimation based Approach: In this method both input and output data from the plant are used to estimate the parameter of interest. If the parameter represents the value of any physical quantity (say resistance, inductance etc of an electric circuit) then any deviation of the parameter from nominal value can be recognized as a fault. Otherwise, we need to know a relation describing how the estimated parameter is related to the physical parameters or component values of the plant.

(2) Observer based approach: In this method dynamic observers, like Luenberger or Doyle-Stein, are applied to compute the complete or a part of the state vector of plant. The observed state vector is compared with the actual state vector of the plant to derive the residual signal. Unknown input observers are employed which are robust against unknown inputs acting on the plant [94]. Number of observers to be employed depends on the number of faults we want to isolate simultaneously. Multiple observers are very effective in isolation of faults when there are faults in single or multiple components.

(3) Parity space based approach: This is an input output based method where the relations between inputs and outputs are used to derive the residuals [46]. The residuals are transformed to eliminate the state signals. This transformation is done by using a parity space matrix which lies in the null space of the observability matrix [27]. Proper design of the parity space imparts necessary properties in the residuals which makes fault isolation possible. Also disturbance rejection can be made possible by suitable choice of parity space.

(4) Kalman filter based approach: Kalman filter is an observer which optimally eliminates measurement noise. Kalman filter estimates the states of the plant with minimum variance when statistical properties of the noise are known [52]. Prediction errors or innovations of Kalman filter can be used for diagnosis of faults. In the absence of a fault, the innovation is zero mean and white. So stochastic techniques can be applied to diagnose faults. Fault isolation is difficult since multiple Kalman filters are required to isolate the faults. Each filter is matched to a particular fault.

Research works of Patton and Chen have shown that parity space based approach is similar to observer-based approach where the observer is a dead-beat observer. This work is referred in [38]. Gertler has shown similarity between parameter estimation scheme and parity equation based approach [45].

Analytical Redundancy techniques depend on the mathematical model of the plant. Thus in general these techniques are susceptible to modeling errors and high computational burdens. Errors in the mathematical models reduce the sensitivity of the fault detection algorithms and also cause false fault alarms.

The methods described above have their own limitations. The accuracy of the estimation depends on the nature of signal applied to the plant. Unless the signal is persistently exciting, the parameters cannot be estimated accurately. In a real application it is not always possible to apply persistently exciting signal to the plant. Generally the parity space based method is affected by noise as the method uses higher order derivative of the signals. State variable based signal processing has been advised by many authors to reduce the effect of noise. The Kalman filter and Observer based approaches are mainly threshold-based approaches where outputs predicted by the filter or observer is compared with the actual output of the system to generate residuals. In this approach, to isolate a particular fault we need an observer or filter based on that fault model of the system. Thus the number of observers becomes very large when we want to isolate a large number of faults.

1.4 Controller reconfiguration for performance restoration

Controller reconfiguration is needed to compensate the effect of fault. After the diagnosis of a fault a new controller is applied so that the faulty system behaves as closely as possible to the healthy system. Controllers can be scheduled from a bank of controllers designed offline for all possible faulty situations. This is similar to the gain scheduling approach applied in aerospace vehicles where a particular controller gain is applied for a particular aerodynamic condition. Since the number of controllers designed offline is finite, fault coverage should be studied thoroughly. There should be sufficient number of controllers so that they can cater to all possible faults. Robust controller design can be achieved for fault tolerance through linear matrix inequality approach.

Online design of controllers represents a recent trend in the field of controller reconfiguration. Controller is designed using the fault related parameters like the location of fault and intensity of fault. One of the well-known methods in case of actuator failure is pseudo inverse method or the control distribution concept [115,17]. Once the control allocation matrix of the faulty system is known, control signal can be derived in a way such that it produces the same effect as the nominal controller had produced on the healthy system. Computation of the control signal involves calculation of the pseudo inverse of the control allocation matrix of the faulty system.

Feedback linearization technique is a method to linearize a non-linear system with out any approximation, so that an exact linear controller can be designed for the system. Control distribution can be applied along with feedback linearization for fault accommodation in a non-linear system. Model-following technique is applied in aerospace application to make the faulty vehicle follow the desired trajectory. In this method a quadratic function of the error between actual and desired state is minimized.

1.5 Research in FTC

Research works in fault tolerant control began in early 1970's. Fault accommodation in linear systems was studied by Beard using self-organization [7]. At the same time Jones tried to accommodate faults in linear systems [65]. During 1980's a number of researchers contributed in the field of fault tolerant control. Frank carried out fault diagnosis in dynamic systems using state estimation approach [37]. Frank and Wunnenberg used unknown input observers for fault diagnosis [40]. Extended Robust Observer based schemes were studied for fault isolation by Ge and Fang [43]. Isermann studied application of parameter estimation scheme in process fault diagnosis [59,60]. Chow and Willsky used analytical redundancy based techniques and established parity space based fault detection and isolation method [27]. Optimal residual design was applied for model based fault diagnosis by Casser et al. [23]. Model based FDI which caters to unknown load torque, and un-modeled dynamics have been developed for a benchmark problem of a diesel engine actuator by Blanke et al. [9]. Bogh has implemented FDI with a bank of non-linear observers. Faults have been discriminated from unknown inputs by multiple hypothesis testing [15]. Faller and Schreck reviewed the possibility of nueral network based technologies for solutions of complex aeronautical problems including fault detection [35]. Yan, Sunderrajan and Saratchandran studied the fault tolerant flight controller using minimum resource allocation networks [133]. Pashikar et al. have shown that addition of a neural controller to an existing controller can improve landing capabilities of a fighter aircraft in presence of severe stuck faults in control surfaces. They have applied Extended Minimal Resource Allocating Network which uses only on-line learning [92]. Napolitano et al. have described a neural network based fault tolerant system which can accommodate both actuator and sensor faults. It uses a main neural network and a set of decentralized neural network to detect a wide variety of sensor faults [85]. Actuator fault is accommodated using three neural controllers using the main neural network. Using analytical redundancy, a bank of extended Kalman filters and a network of cross checks have been developed by Zolghadri for safety management in a civil aircraft [145]. Mapping between faults and their symptoms using back propagation and Elman type neural network has been studied by Lei et al. [73]. Q.Zhao and Jiang designed reliable state feedback control capable of tolerating actuator failure [142]. They also studied recomputable control scheme under imprecise fault identification [64]. FDI for non-linear systems modeled as polynomial differential-algebraic equations is solved by Ritt's algorithm [137]. A bank of EKF has been applied for actuator fault diagnosis in an unmanned underwater vehicle by Alessandri et al. [2]. They have applied one filter for each fault and also one for the healthy model. Dedicated observer scheme (DOS) with periodic resetting for FDI in systems which are not observable from the point of view of DOS, has been studied by Aguirre and Preira [1]. Continuous fault monitoring for detection and control was studied by Grimble [50]. Simultaneous detection and isolation of faults have been studied by Bloch et al. by robust parameter estimation [12]. This work led to the development of the fault tolerant control schemes for application to aerospace and process industries. Fault detection in linear periodic system has been studied by Zhang and Ding using a periodically varying parity vector approach [136]. They have studied the relation between this type of parity vector and periodic observer. The condition for disturbance rejection has also been investigated in this work.

Researchers in the field of Fault Tolerant Control (FTC) have used a wide range of techniques like the simple threshold detection, employment of different types of observers, parameter estimation schemes, parity space, LMI based techniques etc. These are all model-based methods. Qualitative and knowledge based methods for FTC employ Neural Network and Artificial Intelligence for detection of faults in non-linear complex systems. Most simple approaches carry out fault detection by comparing measurable quantities with some estimated quantities and reconfiguration is achieved by adding an additive control force on the system which overcomes the effect of fault. Parity-space based approaches which use analytical redundancies have been successfully applied by Chow and Willsky to detect both actuator and sensor faults [27]. Gertler has studied fault detection and isolation for both additive and multiplicative faults using parity space approach [45]. In the work of Gertler, disturbance decoupling and model error accommodation have been considered. Also relation of parity space based approach with diagnostic observers and parameter estimation has been pointed out [45]. Continuous time parity space relation with time delay has been used by Medvedev to detect and isolate sensor and actuator faults [83]. Extended Kalman filter (EKF) based approaches have also become popular for detecting sensor faults [22]. The authors have applied EKF and Robust Kalman filter (RKF) to detect both sensor and actuator faults. The mean of the innovation sequence is used to detect and isolate faults in a non-linear model of an aircraft. They have shown that RKF can distinguish between sensor and actuator faults [53]. Estimation of position sensor bias and actuator current bias by EKF have been investigated by Walker et al. in an industrial actuator benchmark [128]. Hybrid systems, consisting of continuous physical and discrete logical variables can be dealt with Markov parameters and Petri nets to accommodate and tolerate faulty situation [77]. Relation between fault sensitivity and number of principal components has been studied in [119]. In this work the number of principal components that provides maximum sensitivity has been terms as optimal number.

Fault tolerance has received special attention in the area of aerospace research [52]. In aerospace domain fault tolerance is achieved mostly by model based fault detection and isolation. Aravena et al. have investigated fault detection from a series of methods ranging from model-based approach to machine learning based methods [4]. They have applied linear quadratic regulators according to the fault condition to maintain acceptable performance. Schwager et al. have investigated theoretically motivated validation and verification techniques for adaptive controllers in the context of controlling uncertain flight vehicle dynamics [109]. Thomas et al. have investigated regulation of flight path angle and velocity of an aircraft in the event of a partial elevator failure [121]. They assumed that the fault detection and isolation mechanism are present and an appropriate controller is switched which consists of a non-linear regulator and composite observer. A comparison of different active fault tolerant control methods has been done in [141]. In this review practical application techniques have also been discussed.

Patton and Chen have reviewed parity space based fault diagnosis approach with special emphasis on aerospace systems [93]. Residual generation using parity space approach has been recognized as the core element with the main focus on robustness and isolation problems. Potter and Suman have extended the Midvalue Selection Technique to design failure-tolerant strap down inertial systems [100, 99]. In this context they utilized the concept of Parity Space and Parity Vectors. They recognized fault detection problem as an estimation problem where inputs are estimated from noisy measurement of outputs. They considered failures as another kind of noise and suggested design of worst-case estimators that give optimal performance in their presence. Ray et al. developed fault detection and isolation on the basis of parity space approach which seeks systematically the largest consistent subset from a set of measurements [105]. The correct estimate of the measured variable is obtained from the consistent set of measurements, and inconsistent measurements are isolated. Ray et al. have discussed analytical redundancy for fault detection and isolation and suggested techniques for development of real time process models that supplement the sensor redundancy. They have applied the method for on-line detection and isolation of sensor faults in a nuclear reactor [106]. Szaszi et al. gave emphasis on analytical redundancy and suggested modeling of faults in linear parameter varying state space models of aircrafts [118]. Instead of using a family of linear models, the authors proposed to use Linear Parameter Varying (LPV) or quasi-LPV models for failure detection and isolation in aircraft applications. Wang and Lam discussed the issue of fault detection in the presence of uncertainty of the system matrix [130]. In another work Klancar et al. have generated primary residuals from parity relations and removed modeling errors by neural network [70]. They used unconstrained optimization approach to design fault detection observers which are robust against uncertainties but sensitive to faults. Collins and Song used Popov-Tsypkin multipliers to design H_∞ estimates for robust fault detection [29]. They have shown that the H_∞ estimator based fault detection technique is less conservative than existing small gain theorem based methods and is capable of detecting both hard and incipient faults. Shen et al. have addressed multiple fault isolation in an eigenstructure and developed a parametric characterization of all allowable eigenspaces [110]. In another work Shen and Hsu have introduced unknown input fault isolation observer by eigenstructure assignment [111]. Eigenstructure assignment approach for observer based FDI has been examined by Jergensen et al. on an industrial actuator benchmark [62]. Tarantino et al. have applied generalized Luenberger observer for fault detection filter design [120]. They have discussed a diagnostic observer capable of multiple fault isolation and claimed that the method is robust against unstructured uncertainties but sensitive to faults. Shoureshi and Hoskin have used model-based technique to detect and isolate faults in systems [113]. Their scheme uses state innovation to detect fault and state solution path to isolate the faulty components. Eigenvalue sensitivity analysis has been used to support the fault isolation problem. Walker et al. developed a scheme for fault tolerant control of Helicopter Swashplate which maintains all the actuators in active conditions so that transient effect can be nullified following a fault [127]. Also the scheme incorporates minimum norm concept which conserves hydraulic energy.

Kim et al. solved the detection and isolation problems of faults in two sensors involving large fault angles using Extended Parity Space Approach [69] and studied this approach to increase the probability of detection and isolation of faults in two sensors. Schram et al. worked on formation of residuals based on parity space approach using a window of input-output information [108]. Maximum degree of freedom is kept for disturbance rejection and parametric uncertainty. Recursive least squares estimation is used to compute parameters from residuals. Kalman filter is used to handle noisy measurements. They have shown their method to be capable of handling multiple failures [44]. Vanderwerf et al. described the Honeywell- Hexad development program which is a refinement of Generalized Likelihood Ratio Test for fault detection in inertial navigation systems [125]. Methods to detect spoofing disturbance in GPS receivers used in conjunction with inertial navigation system have been discussed using interacting multiple model tracker by Oshman and Koifman [90]. They have also shown that this method can optimally estimate the state of the system in the presence of a disturbance [91]. A hybrid fault detection technique for failures in inertial sensors mounted on Unmanned Arial Vehicle (UAV) has been proposed by Kim et al. [68]. This approach combines hardware-based technique with parity equation approach using wavelet analysis. They have also proposed a model-based technique in which residuals are computed using an Extended Kalman Filter. Parity vector based real time FDI in UAV has been attempted by Bo et al. They have used maximum likelihood estimate to correct the fault vector [13]. Geisseler and Besch have discussed detection of oscillatory failure in aircraft control system [47]. They provided a comprehensive study of sources, effects and detection methods of such failures. A calibration procedure for redundant inertial measurement unit used in sensor fault detection has been described by Cho and Park [26]. By calibration they meant evaluation of coefficients of sensor errors to compensate them. Szaszi and Balas extended fault detection and identification technique for linear time invariant systems to linear time varying systems [118]. They have applied their technique to actuator failure in a closed loop linear parameter varying system. Physical diagnosis of turbojet engine by robust parameter estimation has been discussed by Grodent and Navez [51]. They have suggested Bayesian approach for robust parameter estimation. Fault is detected by comparing the estimated parameters with nominal values of parameters in a statistical framework. Chen et al. introduced frequency dependent weighing factor based performance indices (cost functions) to robustly detect sensor faults in the presence of modeling uncertainty [25]. Multi-objective optimization is solved via genetic algorithm to calculate the cost functions. Brandeau and DeCanio have discussed the use of fault tolerant digital computer for application in military aircraft needed to be operated with high maneuvering under very adverse situations [20]. In the field of electromechanical actuators Annaz has investigated FDI by hardware redundancy and intelligent monitoring. Load distribution and force fighting reduction have been solved in the same work [3]. Systems suffering from intermittent faults can be modeled as discrete event systems and are difficult to observe. Contant et al. have found out necessary conditions for diagnosis of this type of faults [30]. Delaet and Tixeuil proposed an algorithm that tolerates both transient and intermittent faults in a distributed communication system comprising of processors and communication lines [31]. Parametric faults in continuous time multivariable systems have been detected and isolated by Li et al. using Optimal Primary Residuals. This approach results in a constant fault model. Fault isolation is possible by transforming the residuals in a structured form [74]. Using a bank of isolation estimators Zhang et al. have attempted fault isolation in a class of non-linear input-output systems with unstructured modeling uncertainties [138]. Noura et al. have investigated fault tolerant control by applying a new control law after on-line estimation of faults. Delay reduction has been achieved by modifying the basic method. They have demonstrated the method on a three-tank system [89]. Using singular value decomposition Maryak et al. have found out relation between observed data and nominal system. This has been utilized for FDI. Using an adaptive threshold technique, false alarm has been avoided [82]. In order to apply FDI to a non-linear process Gatzke et al. have applied multiple linear models. Parameter estimation has been applied for FDI [42]. Single and multiple sensor fault isolation have been done using extended observability matrix and lower triangular block Toeplitz matrix by Li and Shah [75]. This was achieved by adapting structured residual approach. Observer based fault detection in gyroscopes using eigenstructure assignment has been investigated by Venkateswara et al. for spacecraft applications [126]. A classification-based approach has been proposed by Wang et al. for early fault detection and self-recovery in aero engines [129]. They have combined their approach with Stochastic Resonance, Wavelet Packet Analysis and Support Vector machines for fault identification and self-recovery. Recently attitude tracking of flexible spacecrafts in presence of actuator faults and disturbances using adaptive back stepping sliding mode control is addressed in [63]. The scheme does not require explicit fault identification. Subspace predictive control method has been used in [54] to achieve fault tolerant control in presence of unanticipated faults. The predictor is recursively updated to accommodate unanticipated fault. A multiple model-based classifier is used to classify faults into anticipated and unanticipated group. For anticipated faults a fast reconfiguration is proposed for fault accommodation. A nonlinear fault detection and isolation system capable of identifying lock-in-place and floating actuator faults has been developed in [33]. The method has been enhanced by using auxiliary excitation signals and works over the entire operating region of an unmanned aerial vehicle. Boskovic et al. have proposed application of high frequency signal to faulty actuators for fault identification [19]. In their work a health monitoring system isolates the faulty actuators. Then by application of a high frequency signal the rest of the fault related parameters are identified. The effect of this high frequency signal on plant dynamics is minimized by using the healthy actuators. In another work Boskovic et al. have proposed a retrofit control law, that retains the baseline control law, to accommodate severe structural damage [18]. The retrofit control law is active only when the system states leave the nominal set. The proposed method can be applied for non-linear and unstable systems. Pooled nonlinear autoregressive moving average model with exogenous excitation has been applied by Dimogianopoulos et al. for fault detection and identification in aircrafts [32]. They have proposed a direct scheme, which considers the input from pilot/autopilot and a measurable flight-attitude signal as output for FDI. An indirect scheme is also proposed in their work, which involves modeling of interrelationship between a group of flight variables. The methods are applicable over entire flight regime.

In recent years application of adaptive control algorithm has produced some interesting results and many workers have applied the same to accommodate control effecter failure for assuring safety in military aircrafts. Narendra and Annaswami showed that conventional adaptive control algorithms work satisfactorily only under certain assumptions, and their stability cannot be guaranteed under arbitrary and sudden changes in the plant [86]. This difficulty was circumvented by Narendra and Balakrishnan by applying multiple models running parallel to the plant [87]. Narendra and Xiang applied the same scheme for discrete time systems [88]. These models work as fault observers in either fixed or adaptive mode and present the environment of the plant at any instant. Boskovic et al. have applied this technique for different complex actuator-failure detection in military aircraft and spacecraft [17]. Fault tolerant control in presence of actuator faults and bounded unknown disturbances have been studied in [143] using direct adaptive state feedback control. A class of controllers is constructed using adaptive scheme and stability of the closed loop system is guaranteed using Lyapunov stability theory.

Detection and isolation of faults in complex non-linear industrial processes is a challenging task and researchers rely on data driven soft computation methods like Artificial Neural Networks and Fuzzy Logic [14].

If the model is not exact then discrepancies between the model and real system can be overcome by unknown input observer approach which considers discrepancies as unknown inputs and the observer is made insensitive to these unknown inputs. Literature in fault detection and identification is rich in linear observer theory and extension has been done to non-linear observers. But one needs to have a proper mathematical model of the non-linear behavior. This restricts the application of model-based approach of FDI to certain class of known non-linear processes. Recently European Union (EU) has carried out research works on actuator fault detection and identification under EU Framework 5 Research Training Network. The objective was to seek for Development and Application of Methods for Actuator Diagnosis in Industrial Control Systems (DAMADICS) coordinated by the University of Hull UK, during 2000–2004. Researchers have applied different soft computing methods like Neural Network, Fuzzy Logic, and Pattern Reorganization, to detect both abrupt and incipient faults in process actuators [21].

Bartys et al. studied the actuator benchmark used in fault diagnosis studies [5]. These authors expressed that both supervisory diagnostic system and local intelligence is needed for advanced diagnostic capabilities. A benchmark problem on electromechanical position servo for speed control of diesel engine has been described by Blanke and Patton [11]. Structural analysis is a powerful tool for early fault detection and isolation. Dustegor et al. applied structural analysis to improve fault isolability [34]. Supavatanakul et al. used timed automation to model discrete event system [117]. They have used measured input-output signals to determine presence of faults by incorporating knowledge of faultless and faulty system. Passive approach based fault detection and isolation has been studied by Puig et al. [102]. In this method uncertainties are allowed to propagate in the residuals and robustness is achieved by using an adaptive threshold. The authors have included some non-linearities of real system and designed non-linear interval observer. Patton and Hou proposed fault detection and isolation observer by decomposition of an extended matrix pencil. Component, sensor and actuator faults have been treated in a unified manner [95]. Squared Coherency Function (SCF), sensitive to change in plant dynamics, has been applied by Pervidi and Parisini for a benchmark problem on actuator fault detection [101]. The authors have assumed that the fault free plant is linear and fault creates a non-linear dynamical perturbation on the linear model. The effect of non-linearity could be estimated by computing SCF using input-output data of the plant. Koscielny et al. addressed the problem of distinguishability by multiple valued evaluations of symptoms [71]. The authors have addressed a general view of the fault distinguishability problem. Fuzzy classifier based identification of symptom space corresponding to different categories and fine precision discrimination inside overlapping areas have been utilized by Bocaniala and Costa for fault detection and isolation [14]. To overcome the problem of unknown model structure, non-linearity in parameters and unknown noise level the group method data handling (GMDH) neural network has been used by Witczak et al. [132]. Calado et al. applied fuzzy qualitative simulation algorithm to detect fault [21]. They applied hierarchical structure fuzzy neural network to isolate faults. In another work qualitative observer based qualitative reasoning is proposed for FDI by Zhuang and Frank [144]. Neuro Fuzzy and De-coupling Fault Diagnosis Scheme which applies multiple observers corresponding to multiple faults and operating conditions generating multiple residuals have been applied by Uppal et al. to detect and isolate faults [124]. Persis and Isodori introduced the notation of observability codistribution of a non-linear system [96]. This is an extension of the complementary observability subspace. They have shown that observability codistribution concept can be applied to solve the fundamental problem of residual generation (FPRG) in fault detection. The FPRG states that residuals should be sensitive to faults but immune to disturbances. In another work they have addressed the problem of non-linear fault detection and isolation using differential geometric approach. The solution of the problem has been characterized using certain distributions. This distribution is analogous to the unobservability subspace of linear systems [97]. The geometric approach has been applied for fault detection and isolation in a vertical take off and landing vehicle [98]. Fault detection in air-conditioning systems has been addressed in the review articles [66,67] where strengths and weaknesses of different methods of fault identification have been addressed. Theses methods include different model based approaches and soft computing approaches.

1.6 Motivation behind the work

The above review indicates that there exists a vast amount of literature on fault tolerant control studies. Despite that, there are problems that deserve particular attention. One of them is the isolation of simultaneous faults in multiple actuators. This problem becomes challenging when there is complete redundancy in the actuation system, as the redundant actuators behave identically. Also detection of serial faults and recovery of faults have not been addressed adequately in the literature. Although some works have already been carried out in this area, these appear to involve excessive computations for practical applications. In this work we have concentrated on actuator faults and addressed the problems of serial faults, simultaneous multiple faults and recovery of faults limiting the work within the domain of actuator faults. We shall now discuss about the different types of actuator faults and specify those that have been considered for study in this work. Also we shall discuss the challenges associated with isolation of faulty actuators under redundancy.

1.6.1 Actuator faults and their effects

The actuators are the workhorses of the control system. They receive commands from the controller and amplify the command to generate control effort on the plant. This control effort can be force, torque, voltage, current etc. When actuators under go fault they become unable to apply this control effort according to the command they receive from the controller.

There are various types of actuators used in industry like electric, pneumatic, hydraulic, electro hydraulic, electro-pneumatic etc. Other than these recently piezoelectric actuators are finding their application in aerospace application and in the area of vibration control. The most common type of actuator used in process and aircraft industries are the electro-hydraulic and electro pneumatic actuators. The electro hydraulic actuators generally consist of an electric motor driving a pump to pressurize a liquid which may be a mineral oil stored in a reservoir. A valve whose position is controlled by a controller controls the flow of the liquid in a chamber called actuator chamber. When the pressure of the liquid flowing in the actuator chamber exceeds the friction of the piston of the actuator chamber, the piston will move. Similar type of arrangement is found in electro pneumatic actuators, where pressurized stored gas is used instead of liquid. Suppose we want to control the flow of some fluid using a valve. The valve is connected to a pneumatic chamber by a spring-loaded rod whose top end is attached to a diaphragm. Gas pressure on the other side of the diaphragm is controlled by an electrical arrangement, say a solenoid coil. By varying this pressure the rod is displaced and the valve position is also varied accordingly. Thus the flow of the liquid is controlled.

Several types of faults can occur in the electro-hydraulic actuators. There may be leakage in the sealing system, degradation of oil bulk modulus due to heating over time, etc. Also degraded seals may increase coulomb friction. The burnt liquid has a different viscous friction than a fresh one. Similarly, over heating of the liquid may produce solid particles which may clog different components such as valves. The motor and the pump can also undergo different faults like short circuit in windings, wear out of gears, breakage of link to motor, seal wear etc. Electro pneumatic actuators undergo similar type of faults like clogging of valves, perforation of diagram, spring fault, external leakage, twisted link rod etc.

All of the above mentioned faults change the behavior of the actuators. This behavioral change can be classified into loss of effectiveness and stuck of actuators. When there is a leakage of fluid or change in the characteristics of the same, actuators need larger command than a healthy actuator to generate the same actuation force on the system. So this is loss of effectiveness. Loss of effectiveness may also result from motor winding shortage, spring malfunction etc. On the other hand clogging of a valve or displacement of a gear may result in complete stagnation of the actuator. In this condition the actuator is unable to follow any control command. This type of fault is called stuck fault. Apart from these types of faults there can be erratic movement of an actuator though this is very uncommon.

The effect of these types of faults on the system can range from sluggish response to catastrophic failure. When loss of effectiveness is not very high the controller can still satisfy the control objective due to robustness. But after a certain magnitude, the loss of effectiveness induces an unstable condition. The effect of stuck fault is much more severe as it makes the actuator completely incapable. More over the stuck actuators generate unwanted force on the system which is a disturbance. Stuck faults can easily create unstable condition and thus results in catastrophic failures.

In this work we have considered both loss of effectiveness and stuck of actuators. Loss of effectiveness can be modeled as a multiplicative fault, where in the state space model of the system the column of the control allocation matrix corresponds to the faulty actuator is multiplied by a scalar less than 1. Thus the problem of identification of loss of effectiveness is a parameter estimation problem.

In case of stuck fault the faulty actuator behaves as if it is driven by a constant command, which cannot be varied by the controller. Thus stuck fault is modeled by driving the system input corresponding to the faulty actuator by a constant input completely uncoupled from the controller command. The problem of identification of stuck fault is closely related to a signal estimation problem.

We shall also study fault tolerant control of the plant under loss of effectiveness and stuck condition of actuators. Reconfiguration of the controller based on the nature of the fault is a direct method for fault tolerance. Also the control objective can be satisfied if the total control force needed on the plant is distributed among the healthy actuators. This is known as control distribution and does not require designing a new controller. In our work we have applied both of the methods to achieve fault tolerance.

1.6.2 Fault Models for FDI

Fault Detection and Isolation are essential tasks for Fault Tolerant Control. Modeling of faults is essential for designing an FDI system which uses model based approach for FDI. Faults can be modeled as additive signals or as changes in system parameters. It is generally believed that models for FDI are as complex as the models used for control. But Frank et al. have proven that characteristics of the models for FDI are less complex than the models used for control [39]. This is because we restrict the fault models to a location where the fault is supposed to occur. Practical systems are non-linear in nature. But for the sake of analysis they can be modeled as linear systems around operating points. These linear models are valid so far as the deviation from the operating point is not large. For example, angular motion dynamics of a satellite launch vehicle can be modeled by a set of differential equations expressed in state space form. Fault models are chosen by considering the type of plant, available measurement, nature and number of faults to be isolated.

Systems can be modeled both in the frequency domain and time domains and faults can also be modeled accordingly. Zhang et al. adopted frequency domain approach for fault detection and isolation in a sampled data system [135]. They also considered decoupling of unknown disturbance. Frequency domain models are particularly helpful when spectrum of a signal contains information regarding faults. Also parity equations of the time domain can be converted into those in the frequency domain. But FDI is always considered as a real time task, and as a result time domain models are widely used for analyzing fault tolerant systems. Moreover, state space based models are very convenient for analyzing Multi Input Multi Output (MIMO) systems. So they have found wide applications in FDI.

The state space model for a linear time invariant MIMO system is given by the following set of equations,

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) + \mathbf{D}\mathbf{d}(t) \tag{1.1a}$$

and

$$\mathbf{y}(t) = \mathbf{C}\mathbf{x}(t) + \mathbf{n}(t), \tag{1.1b}$$

where $\mathbf{x}(t)$ is an n dimensional state vector and $\mathbf{u}(t)$, a p dimensional input vector. Here the vector $\mathbf{d}(t)$ denotes the external disturbance. The dimension of $\mathbf{d}(t)$ depends on the number of sources of disturbances. The vector $\mathbf{y}(t)$ is a q dimensional output vector and $\mathbf{n}(t)$ is a q dimensional measurement noise. The matrices **A, B, C** and **D** represent plant dynamics, control allocation, output measurement and disturbance distribution respectively.

Any fault in process is modeled as change in the **A** matrix. Actuator faults are parametrically modeled as the perturbation in **B**, whereas sensor faults can be modeled as changes in the **C** matrix. So under all possible faults, the system represented by Equations (1.1a) and (1.1b) is given by

$$\dot{\mathbf{x}}(t) = (\mathbf{A} + \boldsymbol{\delta}\mathbf{A})\mathbf{x}(t) + (\mathbf{B} + \boldsymbol{\delta}\mathbf{B})\mathbf{u}(t) + \mathbf{D}\mathbf{d}(t) \tag{1.2a}$$

and

$$\mathbf{y}(t) = (\mathbf{C} + \boldsymbol{\delta}\mathbf{C})\mathbf{x}(t) + \mathbf{n}(t) \tag{1.2b}$$

Here $\boldsymbol{\delta}\mathbf{A}$, $\boldsymbol{\delta}\mathbf{B}$, and $\boldsymbol{\delta}\mathbf{C}$, represent changes in the corresponding matrices due to fault. Representation of faults by additive signals is given by

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) + \mathbf{F}\mathbf{f}(t) + \mathbf{D}\mathbf{d}(t) \tag{1.3a}$$

and $$\mathbf{y}(t) = \mathbf{C}\mathbf{x}(t) + \mathbf{f}_s(t) + \mathbf{n}(t) \tag{1.3b}$$

Here $\mathbf{f}(t)$ and $\mathbf{f}_s(t)$ are process and sensor fault signals respectively. Matrix $\mathbf{F}$ is the fault distribution matrix.

The research work presented in this thesis focuses on Fault Tolerant Control in presence of actuator faults. Actuator faults are mainly of two types. One type is loss of effectiveness modeled by parametric changes in the system presented by the equation (1.2a) with change in only matrix **B** or by additive signal given in equation (1.3a). There is another type of actuator fault called stuck of actuators modeling of which needs both parametric changes and additive fault signal. Suppose the *i*-th actuator got stuck up and $\mathbf{B}_i$ is the control allocation matrix with *i*-th column replaced by zero elements. If $\mathbf{b}_i$ is the *i*-th column of the control allocation matrix of the healthy system and u_i is the stuck value, then the model of the plant under stuck of *i*-th actuator is given by

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}_i\mathbf{u}(t) + \mathbf{b}_i u_i \tag{1.4}$$

Identification of stuck faults comprises identification of *i* and estimation of u_{i}.

It is worth mentioning that the models discussed in this section are chosen from the point of view of detection of fault using a dynamic model of the system. Empirical models derived using data driven approach play a major role in fault diagnosis for systems where detailed dynamics is unknown. An example of this type of model is multivariate regression model derived using input, output and other parameters affecting a systems operation.

1.7 Challenges associated with Actuator Fault Isolation

We now discuss the challenges associated with isolation of faulty actuators from the viewpoint of the degree of redundancy in the actuation system. This is important since the object of this work is to develop fault tolerant control methods of a system in presence of actuator faults and faults can be accommodated only when some level of redundancy is present in the system. On the other hand, redundancy makes the task of isolation of faulty actuators difficult, as the remaining healthy actuators will tend to mask the faulty behavior. However, isolation of faulty actuators is an important step in fault accommodation. In the following discussion we analyze the degree of redundancy using the rank condition of the control allocation matrix of the system. We classify redundancy into two categories given below

(a) **Category 1:** Redundant actuators are used for reliability and fault tolerant control. It can happen that different actuators are physically arranged in such a way that all of them apply control effort differently, but control effort of a single actuator can be generated by a combination of a group of other actuators. Example of this type of actuation system is an aerospace vehicle whose attitude is controlled by four thrust vectoring nozzle or aerodynamic fins. Though individual nozzles or fins generate control force in different directions, control effort of any one of them can be substituted by the combined effect of the other three. Let us consider a linear time invariant system to describe this type of system. When there is a redundancy in the actuation system the control allocation matrix **B** will not have full column rank. Let **B** be given by

$$\mathbf{B} = \begin{bmatrix} a_1 & a_2 & 0 & 0 \\ 0 & 0 & a_3 & a_4 \\ a_5 & a_6 & a_7 & a_8 \end{bmatrix}.$$

Thus maximum column rank of **B** is 3. Thus effect of any actuator can be replaced by the other three. But in general the first and second columns will not be collinear and so will be third and fourth. Thus no actuator can be made redundant by a single another one. For this case all the columns of **B** will orient in different directions in the space they span. Thus all the actuators will have different controllability indices.

(b) **Category 2:** Many systems use multiple actuators, which work in parallel. For example a movable antenna may have two motors for azimuth rotation and two for elevation movement. Each of the two motors for motion in azimuth have identical effect on the antenna, thus their effect is indistinguishable from each other. Another example of this type of redundant actuation system is a Variable Air Volume Air conditioning System, which has been studied in this thesis. In this system any air-conditioned zone is supplied with cold air through multiple Variable Air Volume Boxes whose effects are parallel to each other. When this type of systems is modeled in state space form the actuators operating in parallel are represented by the columns of control allocation matrix, which are collinear. Let us consider a two dimensional system with four actuators. Let the control allocation matrix be given by

$$\mathbf{B} = \begin{bmatrix} a_1 & a_2 & 0 & 0 \\ 0 & 0 & a_3 & a_4 \end{bmatrix}.$$

Under all condition the first and the second columns are collinear and also the third and fourth columns are collinear. This shows that the second actuator is completely redundant to the first one and so is the fourth to the second one. In this case the controllability index of the first actuator is equal to the third one. Also the controllability index of the third actuator will be equal to the fourth one. Here a single actuator is redundant to another actuator.

When a system has **Category 1** redundancy in the actuation system, irrespective of the command generated by the controller for the actuators they have distinguishable effect on the system. Exploiting this we can generate vector residuals each of which will align in a reference direction under a fault in a particular actuator. Each of these reference directions is a function of the particular column vector corresponding to the actuator presented by the column. Since the columns are aligned in different directions in the space they span, the reference directions are also different. Thus single faults in actuators can be isolated. Now for multiple faults in actuators, the same vector residuals will lie is a subspace of multiple reference directions. Since the references have different directions many of these subspaces will not overlap, resulting is possibility of isolation of multiple actuator faults. This enables one to isolate much larger number of faults using relatively small number of fault models of the system. Of course if some of the subspaces overlap we cannot isolate the faults in actuators corresponding to those subspaces.

When a **Category 2** redundancy is present any two actuators, which are mutually redundant to each other, have identical effect on the system. It is natural for a controller to generate equal command for the mutually redundant actuators. Thus it is difficult to distinguish between them. The above mentioned directional residual based approach will not work for isolating faults in actuators having **Category 2** redundancy since the columns of the control allocation matrix corresponding to these actuators are oriented in same direction. To isolate actuator faults we need to apply a dedicated fault identifier for each type of fault, single or multiple, which is possible in the system. So the number of identifiers required is equal to the number of faults which can occur in the system. Also when equal command signals are generated for the completely redundant actuators these identifiers may behave identically resulting in erroneous fault isolation. Thus perturbation is to be induced on the controller generated commands for accurate fault isolation.

Detection of serial faults sometimes becomes difficult when a performance index is used to capture the effect of fault. If a performance index, containing an integral term is chosen which accumulates the fault feature, then it needs to be reset after each fault. Also the current fault model is to be assumed as the nominal model of the plant to detect the forthcoming fault. Similar situation arises when a recursive filter (say Kalman filter) is used to detect serial faults. Unless the filter gain and covariance matrices are reset after each fault, the subsequent faults may not be detected.

One of the major challenges in FTC is estimation of fault related quantities for multiplicative faults in the absence of persistently exciting input signal which needs to be addressed quite seriously. Let us consider the fault model of a system presented by Equation (1.2). To identify the faults we need to estimate the parameters $\delta\mathbf{A}$, $\delta\mathbf{B}$, and $\delta\mathbf{C}$. It is well established in the literature of system identification that for convergence of estimated parameters to the true values the signals associated with parameter estimation should be sufficiently rich continuously or persistently exciting [81]. This means that the signals should have sufficient number of harmonics present depending on the number of parameters we want to estimate. This condition cannot be fulfilled by many plants under their operating region. Thus researchers have applied small excitations to the plants for the purpose of fault estimation. But this method cannot be applied to plants which need precise control or are safety critical. Generation of residuals for fault detection independent of the plant dynamics is an open area. Hoffling and Isermann [57] addressed this problem for single parameter estimation. This technique needs to be extended for estimation of multiple parameters.

The problem of fault detection in the presence of noise and disturbance has been solved in some works. The number of disturbances, which we can reject, decreases with the increase in number of faults that we want to isolate simultaneously. Examples of these approaches are dedicated observer and generalized observer schemes [38]. There are needs to isolate multiple faults and at the same time reject a number of disturbances. These open problems have motivated research activities in fault detection and isolation with particular focus on fault tolerance in the presence of multiple actuator faults.

Another unsolved problem that has not received much attention in the literature is the detection of fault recovery in the presence of controller reconfiguration. We mentioned earlier that when a fault occurs and gets cleared multiple times it is called an intermittent fault. Bennett et al. addressed this problem for sensor faults in a railway traction system using an observer-based scheme. Measurements of the plant are compared with their estimated values for residual generation [8]. We have found that controller reconfiguration following an actuator fault actually shuts down the faulty actuator. Thus if that actuator recovers to healthy state later, this cannot be detected. This has motivated us to apply for an input signal to the faulty actuator so that its recovery can be detected.

1.8 Contribution and Organization of the Thesis

This thesis aims at developing techniques for accommodation of actuator faults under different situations like, loss of effectiveness when Category 1 redundancy is present and stuck of actuators in presence of Category 2 redundancy. We have also addressed the problem of detection of recovery of actuator faults. The main contribution of this work is discussed below.

(1) **Fault Tolerant Control in presence of Multiple Faults**

FTC in presence of multiple faults is a challenging task and we have addressed the following problems.

(a) **FTC in presence multiple faults using a small number of fault models**.

We have shown that when Category 1 redundancy is present a large set of multiple faults can be identified using only few fault models of the plant by adopting the directional residual approach. Thus FTC can be achieved without heavy computational effort. To this extent directional properties of the residuals have been used to isolate single and multiple actuator faults arising mainly due to loss of effectiveness. This approach has some similarity with Beard's detection filter based approach [7]. However, we have introduced a stage wise search algorithm to isolate multiple faulty actuators. To quantify the loss of effectiveness, fault intensity has been estimated by least squares method from the residuals. The methods developed have been made insensitive to measurement noise and disturbance by suitable filtering technique.

(b) FTC in presence of identical inputs to redundant actuators

Under certain conditions in a system with Category 2 redundancy the controller generates identical inputs for the actuators. This makes identification of the faulty actuator difficult. We have addressed this problem and sought its solution in an Adaptive Interactive Multiple Observer (AIMO) [16] framework. Also it was found out that certain single faults affect the fault models corresponding to multiple faults in such a way that the fault is identified as a double fault. Solution of this problem is addressed in an AIMO framework by an input modification scheme.

(2) Detection of Serial Faults and their Recovery

FTC can be employed by a controller reconfiguration scheme using the fault related quantities. We have shown that reconfiguration of the controller after the occurrence of an actuator fault restricts the controller-generated signals within a smaller subspace than that of a healthy system. In a Multiple Model Adaptive Control framework for fault identification, this makes the nominal and the fault model of the plant currently representing the system, behave identically. Also the reconfigured controller completely shuts down the faulty actuator. Thus if the controller recovers from fault, the recovery cannot be detected. Necessary conditions on input signal have been found under which it is possible to detect such recovery.

The fault detection algorithms have been validated by simulating faults in the second stage of a satellite launch vehicle using its state-space model and in a bilinear model of a variable air volume air conditioning system. The model of the satellite launch vehicle under study is unstable and controlled by the integral of error control law [114] in state-space domain. The model of the variable air volume air conditioning system is a stable one but needs a feedback linearization controller for temperature regulation.

Now we discuss the organization of the thesis and overview the contents of the chapters.

In **Chapter 2** a predictive model based approach is proposed to develop a fault tolerant control scheme for a system with Category 1 redundancy. All the nominal and fault models use the complete state space for fault identification. Directional residual based actuator fault detection, isolation and estimation are discussed in multiple model framework where only a finite number of fixed fault models are used. Since no adaptive model is used, computational complexity is reduced considerably. The stage-wise search based algorithm is used for detection of simultaneous failures in multiple actuators. The method has been made the capable of disturbance and noise rejection by proper filtering and transformation of the residuals. It is extended to detect and isolate actuator stuck fault. The developed method is applied to study fault tolerant control of a linear model of a satellite launch vehicle having Category 1 redundancy and encouraging results are obtained.

In **Chapter 3** a parity-space based residual generation approach has been used in multiple model framework for detection of actuator failures in a system with Category 1 redundancy. The method utilizes input-output data instead of the complete state measurement. It is shown that detection of actuator failure can be made possible by comparing the norm of the residual vector against a threshold. It is analytically shown that one can identify the faulty actuator by observing the direction of the residual vector. It is further proven that the residual vector lies in a particular direction for loss of effectiveness of a particular actuator. Multiple fault isolation is made possible by stage wise search among the actuators. With this analysis parity-space based approach has been applied in multiple model framework. An integral form of the parity relations is proposed which is more immune to measurement noise than conventional differential form of the parity relation. We have achieved performance restoration by control distribution among the healthy actuators. The algorithm was tested on the linear model of the satellite launch vehicle and results were quite satisfactory.

The methods developed in Chapters 2 and 3 mainly detect faults using directional properties of residuals for system with Category 1 redundancy. Therefore there is a need to address the isolation of faults in a system with Category 2 redundancy. This type of actuator faults have been identified in **Chapter 4** using Adaptive Interactive Multiple Observer (AIMO). The AIMO has been extended to a bilinear system and we have identified multiple stuck faults with proper modification of the observer corresponding to single fault. It has been shown that observers corresponding to mutually redundant actuators behave identically under certain situations resulting in erroneous fault isolation. Perturbation of commands is used to isolate faulty actuators which are mutually redundant. The identity of the stuck actuator and the estimated effect of the stuck actuator are used to distribute the required control effort on the healthy ones to achieve fault tolerant control. The simulation results on a VAVAC system have been presented to show the effectiveness of the method.

In **Chapter 5** simultaneous and serial failures have been studied using Multiple Model Switching and Tuning approach. If a system returns to normal state from faulty state then methods for detection of that recovery have also been studied. It has been shown that the subspace of the controller-generated signal gets reduced due to controller reconfiguration after a fault. This causes nominal and fault models to behave identically resulting in difficulties to detect subsequent faults and their recovery. Necessary and sufficient conditions have been derived to detect serial faults and their recovery for actuator faults. Analytical relation for the errors between the plant outputs and model predicted outputs have been derived and a performance index is defined with a view to detect faults. It has been shown that the proposed algorithm can detect serial faults in the linear model of the satellite launch vehicle.

In **Chapter 6** we make some concluding remarks on the contribution of this work and carefully analyze the limitations of the present endeavor with special emphasis on the future direction of research activities in fault tolerant control.

In **Appendix A** we have described the mathematical model of the satellite launch vehicle and in **Appendix B** we derived the frequency domain properties of the

τ type [107] integrals. This property is used to derive some analytical results of Chapter 3.