CHAPTER 1

INTRODUCTION

1.1 OUTLINE OF THESIS

In recent days, automatic control systems have been implemented in almost all types of Industrial processes as they can reduce the consumption of energy and can save manpower drastically. However, these systems are mostly prone to malfunctions and errors as the human operator interaction is reduced / removed in these systems. Furthermore, unexpected variations in external surroundings or normal wear and tear of the components of the system can make the overall system become faulty.

Due to the advancement of technology in Science and Commerce, there has always been a thrust to improve the efficiency of the Process or System to the demands of end users. In this regard, Fault Diagnosis and Identification (FDI) plays an important role, and has been one of the most concentrated areas of research, design and development.

The concepts of FDI and FTC have gained wide importance in recent years in order to provide higher reliability and safety standards, as well as improving the quality, cost and efficiency of most technical processes [1, 2].
The faults occurring in the system are either due to the malfunctions of the main processing equipment (leaks in tanks, variations in process parameters, like mass flow rate, heat transfer coefficient, gas storage rate, etc.) or in the auxiliary equipment (bias/drift in sensors, actuators, pumps, controller outputs, stuck sensors, actuators and pumps) [3]. The general practice involved in many industries is to isolate the fault after diagnosis. But some faults which can be tolerated [4] under certain conditions have also been considered nowadays whereby the productivity is not affected at any cost.

The proposed research work is thus to develop and implement FDI mechanism for typical systems using Petri nets. The system behavior is modeled as discrete, continuous and hybrid Petri nets which models the system with both normal and faulty behavior of the system. This is followed by analysis of various estimation techniques used to achieve FTC, which is then followed by evaluation of performance measures and model validation using Markovian models.

1.2 FAULT DIAGNOSIS AND IDENTIFICATION

As it is well-known, an FDI scheme has three tasks: (1) fault detection indicates that something is wrong in the system, i.e., the occurrence of a fault and the time of the fault occurrence; (2) fault isolation determines the location and type of the fault (which component has failed); and (3) fault identification determines the magnitude (size) of the fault. Fault isolation and identification are usually referred to as fault diagnosis in Literature by Isermann in [5]. Based on the above classification, FDI often represents the functions including both fault detection and identification, or simply called fault diagnosis.

The existing FDI approaches can be generally classified into two categories: (1) model-based and (2) data-based (model-free) schemes; these two schemes can
Further be classified as quantitative and qualitative approaches. Essentially, a quantitative model-based FDI scheme utilizes mathematical model (often known as analytical redundancy) to carry out FDI in real-time. Four most commonly used techniques are based on (1) state estimation; (2) parameter estimation; (3) parity space; and (4) combination of the first three. Based on the classification by Venkatasubramanian, et al. in [6], a refined classification of the existing FDI approaches is shown in Figure 1.1.

Since most control techniques are model-based, fault tolerant controllers need to be designed based on the mathematical model of the system being analyzed, particularly the post-fault model of the system.

The objective of quantitative methods [7] is to develop and employ mathematical models, theories and/or hypotheses pertaining to the particular phenomenon. The process of measurement is central to quantitative research because it provides the fundamental connection between empirical observation and mathematical expression of quantitative relationships. Here, the research work is based on Qualitative methods [8] as shown by dotted lines in Figure 1.1. Qualitative approach aims to gather an in-depth understanding of human behavior and the reasons that govern such behavior. Qualitative methods, thus investigate the why and how of decision making, not just what, where, and when. Hence, smaller but focused samples are enough, rather than large samples as in the case of Quantitative methods.
Figure 1.1 Classification of FDI methods
1.3 FAULT TOLERANT CONTROL

Modern technological systems rely on sophisticated control systems to meet improved performance and safety requirements. A conventional feedback control design for a complex system may result in an unsatisfactory performance, or even instability, in the event of malfunctions in actuators, sensors or other system components. To overcome such weaknesses, new approaches to control system design have been developed in order to tolerate component malfunctions while maintaining desirable stability and performance properties. This is particularly important for safety-critical systems, such as aircrafts, spacecrafts, nuclear power plants, and chemical plants, processing hazardous materials. In such systems, the consequences of a minor fault in a system component can be catastrophic. Therefore, the demand on reliability, safety and fault tolerance is generally high. It is necessary to design control systems which are capable of tolerating potential faults in these systems in order to improve the reliability and availability while providing a desirable performance. These types of control systems are often known as Fault Tolerant Control Systems (FTCSs) [9]. More precisely, FTCSs are control systems which possess the ability to accommodate component failures automatically. They are capable of maintaining overall system stability and acceptable performance in the event of such failures. In other words, a closed-loop control system which can tolerate component malfunctions while maintaining desirable performance and stability properties is said to be a fault-tolerant control system.

The main contributions of this research work lie in combining FDI and FTC and analysis is based on applying the same on typical event based systems by utilizing the modeling power of Petri nets.
1.4 PERFORMANCE EVALUATION

Performance evaluation aims at analyzing quantitative system aspects that are related to its performance and dependability. Major performance evaluation approaches are measurement-based and model-based techniques. In measurement-based techniques, controlled experiments are performed on a concrete realization of the system using prototypes, and gathered timing information is analyzed to evaluate the performance measures of interest, such as time-to-failure, system throughput, or number of operational components, etc. In model-based performance evaluation, an abstract (and most often approximate) model of the system is constructed that is just detailed enough to evaluate the measures of interest with the required accuracy. Depending on modeling flexibility and computational requirements, analytical, numerical or simulative techniques are used to evaluate the required measures.

In this research work, model based approach has been carried out to evaluate the performance measures of the equivalent models for the systems considered for study in order to check the correctness of the model.

1.5 LITERATURE SURVEY

A detailed survey of methods related to modeling of systems, fault diagnosis and identification, fault tolerance control and performance evaluation was done and the details have been included in this section.

1.5.1 Surveys related to fault diagnosis and identification

Numerous approaches have been dealt in achieving FDI in the past few years. Ramirez-Trevino, et al. in [10] dealt with achieving on-line FDI of discrete event
systems based on modeling the system using Interpreted Petri Nets (IPN). A unique procedure has been used by developing an online diagnoser, which efficiently monitors the system’s outputs as well as handles the normal behavior model to detect and locate faults. FDI achieved using the scheme of structured residual approach for a Multi Input Multi Output (MIMO) process has been proposed by Asokan, et al. in [11]. Here, techniques such as residual generation and evaluation have been considered to detect multiple faults based on state space model derived from first principles. The concept of achieving FDI for non-linear systems using observer based approach was given by Rincon, et al. in [12] wherein two schemes of nonlinear observers are used to reconstruct the faulty signals to determine fault diagnosability with minimum number of measurements from the system. FDI along with isolation based on model checking technique using a timed automaton was described by Simeu, et al. in [13]. The concepts of fault detection, isolation, estimation and control compensation using analytical redundancy were described by Theillol, et al. in [14].

1.5.2 Surveys related to fault tolerant control

Historically, from the point of view of practical application, a significant amount of research on fault-tolerant control systems was motivated by aircraft flight control system designs [15]. The goal therein, was to provide ‘‘self repairing’’ capability in order to ensure safe landing in the event of severe faults in the aircraft. More recently, the fault-tolerant control problem has begun to draw more and more attention in a wider range of industrial and academic communities, due to increased safety and reliability demands beyond which a conventional control system can offer. The applications include aerospace, nuclear power, automotive, manufacturing and other process industries as discussed in [16-18]. As given in [19], fault tolerance is no longer limited to high-end systems, and consumer products, such as automobiles, increasingly dependent on
microelectronic/mechatronic systems, onboard communication networks, and software, thus requiring new techniques to achieve fault tolerant control.

1.5.3 Surveys related to modeling of systems

Modern technology has increasingly created man-made dynamic systems which are not easily described by ordinary or partial differential equations. Examples of such systems are batch production or assembly lines, computer and communication networks, traffic systems, etc., where the evolution of the system in time depends on the complex interactions of the timing of various discrete events, such as the opening or closing of a valve or the arrival or departure of a job or the initiation and completion of a task or message. The "state" of such dynamic systems changes only at discrete instants of time instead of continuously. Such man-made systems are called DEDSs as referred by Alexander [20], and opposed by the more familiar continuous dynamic systems of the physical world that are described by differential equations [21]. In food industry, many processes are conducted in a batch mode or have a mixture of batch and continuous processing steps. Batch operations are specially suited for small productions, seasonal products, processes involving many steps and/or solids handling, frequent changes in formulation, and production to demand [22].

The various interactions in a batch process system are highly concurrent and their understanding is further complicated by non-deterministic machine failures, uncertainty environment, limited storage capacities, and a high degree of resource sharing. Batch process systems include a number of processing units working in parallel, coupled by the flow of material and energy. The coupling pattern is time-dependent and many system operations are of a discrete nature, e.g. the sequential and procedural aspects associated in processing a batch according to defined recipes while satisfying all the operational constraints, such as overflow of storage,
precedence, utility requirements, interlocks, etc. To understand such a complicated system, appropriate mathematical models were necessary and were uniquely developed by Bonvin, et al. [23].

Hybrid dynamic systems (HDSs) are currently attracting a lot of attention. The behavior of interest of these systems is determined by the interaction of continuous and discrete event dynamics present in the system. The hybrid character of a system can owe either to the system itself or to a discrete controller applied to a continuous system. Several works have been devoted to the modeling of HDSs. From [24], HDSs are defined as a dynamic system that integrates explicitly continuous systems and discrete event systems. The principal physical phenomena that can be present in HDSs and specifications that they can be either autonomous or controlled were given in [25].

1.5.4 Surveys related to Petri nets

Petri nets were introduced in 1962 by Carl Adam Petri [26]. Petri nets are a powerful modeling formalism in Computer Science, System Engineering and other disciplines. Petri nets combine a well defined mathematical theory with a graphical representation of the dynamic behavior of systems. The theoretical aspect of Petri nets allow precise modeling and analysis of system behavior, while the graphical representation of Petri nets enable visualization of the modeled system state changes. This combination is the main reason for the great success of Petri nets. Consequently, Petri nets have been used to model various kinds of dynamic event-driven systems like computer networks as given in [27], in communication systems [28], manufacturing plants [29, 30], command and control systems [31], real-time computing systems [32], logistic networks [33], and workflows [34], to mention only a few important examples.
These systems may be asynchronous and sequential, exhibiting characteristics like concurrency, conflict, mutual exclusion and non-determinism [35]. These characteristics are very difficult to describe using traditional control theory, which deals with systems of continuous or synchronous discrete variables modeled by differential or difference equations. In addition, inappropriate control of the occurrence of events may lead to a system deadlock, capacity overflows, or may otherwise degrade system performance. Hence, Petri net is a very powerful tool in analyzing the characteristics as mentioned above, both mathematically as well as graphically.

Petri nets are a graphical and mathematical tool for the analysis of DEDSs as shown in [36]. As a graphical tool, they can be used as a visual aid similar to flow charts, and as a mathematical tool they can be used to set up state equations representing the system as shown in [37]. Hence, PN concepts can be applied to batch process, modeling and control [38]. The challenge for process control industry, armed with new modeling and control techniques being recently developed, is to achieve sequential control for the batch process plant [39] in order to more precisely define the “best” operating procedures leading to optimal efficiency and plant utilization. Thus, in this research work, attempts are made to utilize the modeling power of Petri nets in the development of a scheme for sequential control of a typical batch process [40] modeled using Generalized Stochastic Petri Nets (GSPN) (class of Timed Petri nets) [41], and an algorithm to achieve fault monitoring offline.

Petri nets as a modeling tool are useful for the study of HDSs [42] because they combine discrete and structural aspects with continuous evolution. Continuous Petri nets [43] are particularly suitable to model flows: liquid flow or continuous production of a machine. However, a flow may be suddenly interrupted: For
example, closing of a valve or a machine breakdown. This is equivalent to having another continuous Petri net. This situation can instead be modeled by a hybrid Petri net containing continuous places and transitions and discrete places and transitions. In addition, in a hybrid Petri net, discrete marking may be converted into a continuous marking and vice-versa.

Earlier Petri nets were used for DEDSs description and analysis [44]. The first steps were taken in [45], by introducing the first continuous Petri net model. Likewise, the hybrid Petri net formalism was introduced in [46]. The hybrid formalism, which represents the continuous flow and a discrete T-timed Petri net were introduced in [47] to represent the behavior of the discrete T-timed Petri net.

The concept of extended hybrid Petri nets were defined in [48] in order to introduce delays and accumulations which allow modeling of batches characteristics and transformations. The first idea of D–elementary hybrid Petri net was introduced in [49], which differs from traditional hybrid Petri net model in the sense that it integrates a T–timed discrete Petri net [50] to describe the discrete part.

1.5.5 Surveys related to performance evaluation

Markov chains are widely used in practice to determine system performance and reliability characteristics. Vast majority of applications considered are Continuous Time Markov Chains (CTMCs). The successful usage of model specification and analysis techniques from concurrency theory for performance evaluation was achieved in [51]. Other related works such as using Stochastic Petri Net (SPN) and its extensions have been discussed in [52, 53]. Merseguer, et al. [54] used the derived SPN from the Unified Markup Language (UML) model to evaluate performance of internet based software retrieval systems. Derivation of an executable GSPN model from a description of a system expressing a set of UML State Machines (SMs) was reported in [55]. A group of works was devoted to
transform the software model to Coloured Petri Net (CPN), which seems to be more related to software properties than the other UML extensions [56-60]. The methods to obtain performance parameters from GSPN to analyze stochastic behavior using embedded CTMC were discussed in [61]. The applications of Markov chains in analyzing the performance of a hybrid Petri net model was discussed by Renato, et.al. [62].

1.6 OBJECTIVES OF THE RESEARCH WORK

From a detailed survey, it was found that the techniques described and proposed earlier were either based on state models developed from first principles using timed automaton or using discrete event systems, wherein the system was analyzed based on their continuous behavior (continuous event systems) or discrete behavior (discrete event system), considered individually. Here, a complete study and analysis along with techniques such as optimization, estimation, observability, etc. are carried out on HDSs, which describe both discrete and continuous behaviors along with their interdependencies.

Initially, the concepts of modeling and FDI are applied on typical DEDSs and results are obtained. Based on the analysis made, the techniques are then applied to a continuous event system considering liquid flow as the major control variable and analytical results are obtained. Further, the techniques are applied on typical benchmark systems (Three tank system) considering it as a hybrid dynamic system along with various case studies, and both numerical and simulation results are obtained. Based on the models developed, performance measures are evaluated to check the correctness of the models developed and simulation results are obtained. Finally, the techniques are applied on data collected from real-time systems for model validation.
The first real time process considered in the work is a Chemical Process, i.e., the Sulphur Recovery Unit (SRU) of refinery process of Chennai Petroleum Corporation Ltd (CPCL), Chennai. SRU unit forms an important and essential unit in refining process, where extraction and removal of sulphur from the products of refining are carried out to improve the purity and efficiency of the products. SRU comprises several sub-units working together to achieve the purest form of the products, thereby reducing the content of elemental sulphur. Here, the working of Main Clause Recovery Concept (MCRC) converters along with the vaporized Liquefied Petroleum Gas (LPG) header unit is considered for study.

Refining process industry comprises various components of boilers, heat exchangers, cooling towers, etc., and the flow of the fuel/gas is done through a series of pumps and valves, controlled through control units placed at various locations in the industry. The control units take appropriate control actions through the help of numerous sensors to control flow, level, pressure, temperature, etc. System normally monitored through automatic/manual means is subjected to frequent malfunctioning and has to be rectified so as to improve the efficiency and to avoid frequent breakdowns. Moreover, the faults or malfunctions that frequently occur in the system are either due to valve or sensor failures. Since valves and sensors are an integrated part of every sub-unit of the process, it becomes quite difficult to identify and detect faults arising due to these failures. Hence, based on the system data collected, algorithms are developed to achieve effective fault diagnosis to detect valve and sensor failures.

Next, the concepts are applied to two sequential processes, i.e., on a typical bottle filling system and a sewage treatment process system to achieve FDI and FTC. The results obtained from the above are highly useful in developing a GUI toolbox in MATLAB environment which gave a total insight into the faulty system along with
the nature of the fault and time of fault using estimation techniques. The main advantages of the proposed research work are

- The basic difficulty of fault diagnosis based on Finite State Automaton (FSA) techniques is state explosion. This is completely avoided here.
- Both Normal and Faulty system behavior can be obtained in parallel using the proposed technique.
- The proposed techniques are qualitative based and do not require an in-depth knowledge of the system under study.
- The proposed techniques are highly useful in diagnosing faults when output is both observable and unobservable.
- Conditions to maintain systems under tolerable limits of working range are proposed.

1.7 OVERVIEW OF THESIS

The thesis is broadly classified into seven chapters. Chapter 1 gives an overview of the need to develop the research along with the problem statement and objectives of the research work carried out and the expected outcome. Chapter 2 covers the theoretical concepts of Petri net modeling along with the details of observability and controllability properties which motivate in building this research work. Chapter 3 gives a total description of the systems considered for study under research work along with the modeling capabilities and analysis. Estimation based techniques to achieve fault diagnosis and identification and fault tolerant control in typical benchmark systems considered are explained in detail in Chapter 4. Chapter 5 covers a detailed description of FDI and FTC achieved in real-time case studies considered for research work. Chapter 6 covers the results and discussions along with performance evaluation for model checking with regard to the systems considered. Chapter 7 presents the conclusions, future scope along with road map developed and followed for completion of this research work in regard to this research work. Finally, the list of references and list of publications are presented.
As discussed earlier, the details regarding the basics of Petri nets, i.e., definitions, representations, properties, etc. for modeling and analysis of event driven systems along with observer and controllability concepts to achieve FDI and FTC are explained in detail in the Chapter 2. These details are highly useful in developing the proposed methodology of estimation based FDI along with FTC.