Chapter 1

1.0 Introduction

1.1 Background

Next generation *mechatronic systems* will require more reliability, availability, safety, embedded control strategy, and configurability in response to provide highly customised products [1]. The benefits that have been achieved so far through implementation of *condition monitoring* [2] are now being significantly extended through the application of new theories, techniques, tools, and methods. Tremendous advances in the field of reliability and availability theory [3], embedded technology [4], soft computing tools and techniques [5], and more importantly the distributed processing [6] have stimulated studies to design as well as realise autonomous machinery systems. It is identified that there now exists new opportunities and challenges, which include the need for more effective ways of designing smarter mechatronics systems.

1.2 Observation

The following section highlights some of the important points as regards to the research trends in the domain of reliability and safety of mechatronic systems.

More detailed information can be found in the literature review chapter as well as in other chapters in the sequel. The presentation described below is entirely based on the observations made by the author by attending numerous conferences and seminars and visiting laboratories nationally and internationally, and reviewing research papers in the areas of Mechatronics and System Design (MSD).

1.2.1 Mechatronics: Mechatronics systems are a class of interdisciplinary engineering systems (Fig.1.1) which entails greater reliability [7]. Bearing in mind that mechatronics is the synergistic integration of mechanical engineering with electronics and intelligent control algorithms in the design and manufacture of products process [8], this dissertation work attempts to present a comprehensive study on Fault Detection and Isolation (FDI) approaches. It is known that control solutions for mechatronics system primarily accommodate two needed attributes such as (i) stable control loops, and (ii) system reliability. While such systems have grown in complexity, stability analysis has become a well established research area since long [9]. Conversely, the research activities on reliability are in progress and continuously improving because of the advancements in new theories, techniques, tools, methods, and technology. Traditionally, reliability was only confined to larger systems like space shuttles, air craft engines, and other similar systems. However, recently its implementation is moving into wider systems, where the impetus is not only bringing about improvement in safety and availability, but also in reducing maintenance costs. The recent developments in soft computing methods and tools [10] and their implementation scenarios have also led to establish a stronger foundation as regards to the development of smarter automated systems.

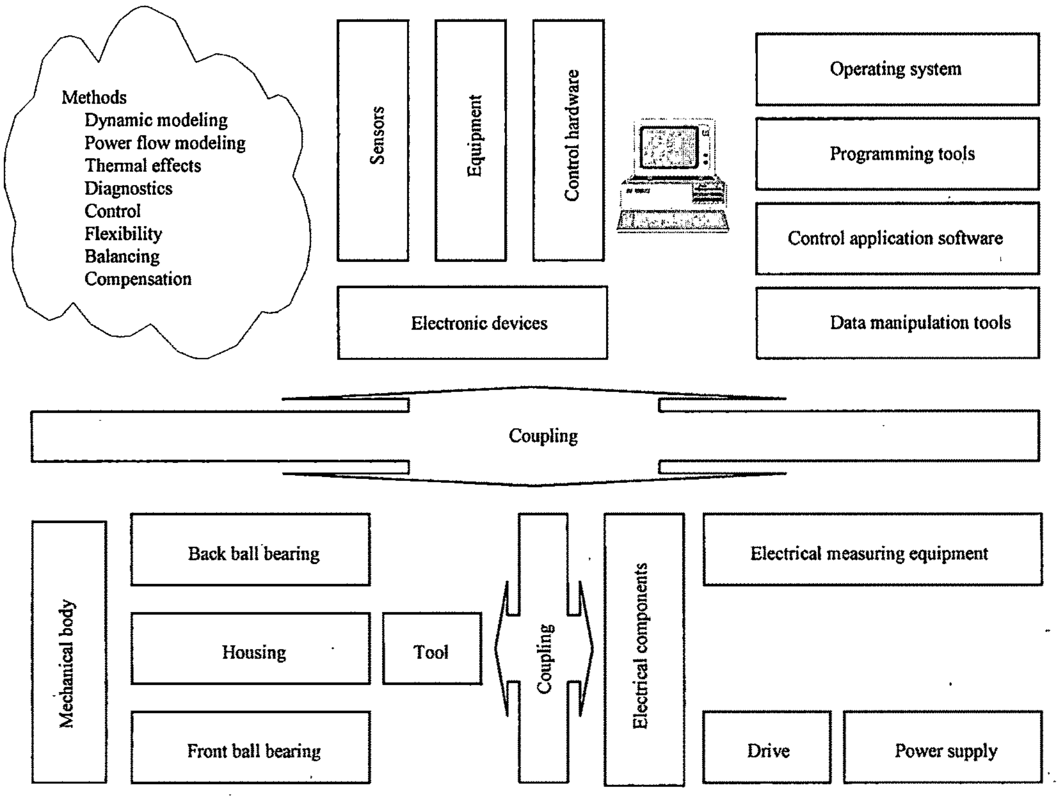

Fig. 1.1: A typical example of mechatronic system: Spindle system

(Courtesy: Mahalik [1])

1.2.2 Reliability and availability: In mechatronics systems, any kind of malfunction is understood as a fault that leads to an unacceptable anomaly in the overall systems performance [11]. Attention has to be paid to this problem in order to meet the demand for safety, reliability, and availability. The qualitative and quantitative indices of reliability have been studied and reported. Reliability is defined as the probability of a system or component to perform a required function under specified conditions for a certain period of time and availability refers to accessibility of the system/component during the acceptance period. As such quantitatively, it is defined as operational use hours of the system/component minus equipment failure down time divided by the operational use hours. Faults may occur in sensors and/or actuators [12]. Such issues are more often not considered in the design and use of traditional mechatronic systems. The development of methods which contribute to the provision of fault diagnosis and fault tolerance is strongly advocated as an essential requirement.

1.2.3 Intelligent control: Total automation means man less plants and the requirement for total automation is the greater intelligence. In the traditional method, conditions of control devices are monitored by skilled operators. But, in this case there is a possibility of human error, which will reduce the efficiency of the plant. Further, a system in which many devices (sensors and actuators) are scattered, they need to be monitored simultaneously. The operator based procedures for such a system are not suitable. Intelligent or smart control systems are those in which, the processing power is incorporated at the device level and soft computing based diagnostic capabilities are built into the devices to improve the overall performance [13]. For more automated application it is thus good to have self-diagnostic devices. In fact, for total automation self-diagnostics of the device is very much essential. Self-diagnostics is a process of assessing the performance of the device with regard to any abnormal situation such as unscheduled shutdowns. Thus, the plant efficiency and the availability of the plant improve and for the same a versatile automatic self diagnostics scheme is needed. Soft computing method uses Artificial Intelligence (AI) tools and techniques such as ALL (Artificial Neural Network) [14], Fuzzy logic (FL) [15], evolutionary algorithms like GA (Genetic Algorithm) [16], and AIN (Artificial Immune Network) [17]. In mechatronics, mainly two types of devices are used. They are sensors and actuators.

1.2.4 Sensor validation: Earlier the sensors were viewed as simple signal generators and were also assumed that the data generated by the sensors were correct. The main subsystems within the structure of a sensor are sensing element, excitation control, amplification, analog filtering, data conversion, compensation, digital information processing, and digital communication processing [18]. The architecture of a traditional sensor is shown in Fig.1.2. But with the emergence of the concept of smart sensors, this architecture has been changed (refer chapter 6). Recent research importance on intelligent sensor is given on assessing the quality of the sensor signal [19]. Control system in a typical mechatronic system requires quality signals instead of simple digital raw signal. The signal generator methods are no longer acceptable. As a matter of fact there has been a trend to design sensor validation algorithm for a wide range of sensors. Note that an intelligent sensor is an extremely complex system. The design, implementation and realization apply a range of disciplines together. With the rapid developments of VLSI design [20], embedded sensors are also developed. It is argued that a standard format must be adopted, and uncertainty should be proposed as a metric of data quality. Some researchers are exploring the physical design based on Microelectromechanical Systems (MEMS) technology [21] with embedded soft-computing diagnostic algorithm using smart materials. MEMS technology integrates mechanical elements on a single chip to make sensors smaller, less expensive and more accurate.

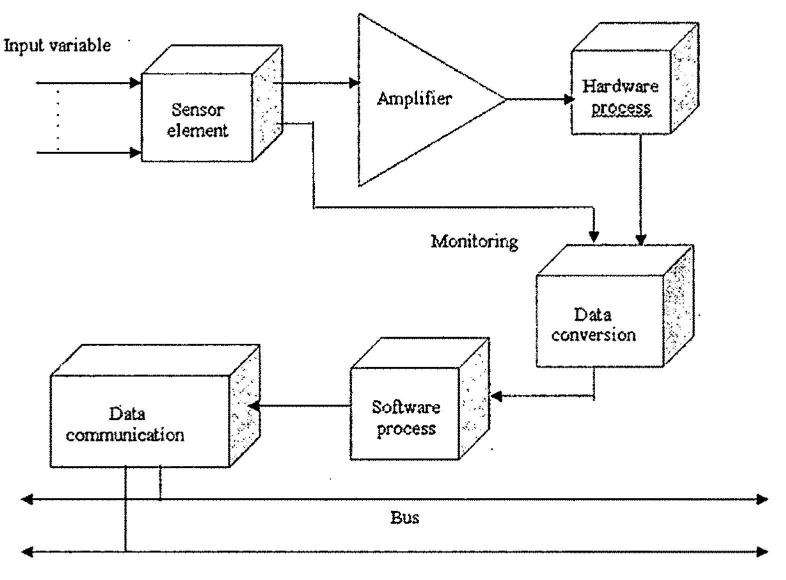

Fig 1.2: Elements of a traditional sensor

There are several methods for sensor validation. In one method either the individual measurements or rate of change of measurements is directly compared with the prescribed thresholds. In this case the switching levels are selected to represent the physical limits imposed by the component specification and operating condition of a process. Another method is the sensor fusion method [22]. Sometimes multiple sensors are used to measure the same measurand. The best one is taken based on the majority voting. Fusion technique is called hardware redundancy.

1.2.5 Actuator validation: The term actuator means converting or amplifying energy from one form to another. It changes the value of a targeted process variable in response to a signal from the control system. An ideal actuator is one which gives static response and has unity gain within an operational range. Outside the range it gives a steady limiting output. A real actuator may have hysteresis, dead zone, curved response, offset and delay etc. Generally, the conventional actuators are troubled by their inherent characteristics and fault conditions. This degrades the performance of the loop. As credible sensing has been a prerequisite for mechatronic systems, actuator validation is also essential. Currently, it is achieved at the device level by adjusting a loop PID regulator, by using auxiliary variables. Applications of soft computing tools and techniques tools play major role in actuator validation. The new generation smart actuators have self diagnostic capabilities and can compensate for the non-linearity and fault conditions for which a generic model and interface for self-validating actuator is proposed [23-24].

1.2.6 Distributed control: There are always two major algorithms developed for mechatronic systems: control algorithm and the FDI algorithm. Both the algorithms are usually developed independently, and individually which are centralised in nature. It means the control algorithm is executed by a central controller. Similar situation is with the FDI algorithm. Separate platform for diagnosis solution and control solution in mechatronics systems can impose extra cost. The integration of control and diagnosis in a distributed technology based platform is beneficial [25]. The performance and efficiency of the system will improve, if the implementation and/or realisation algorithms become more decentralized. This can be thought of as a modular system. It is suggested that the two algorithms: for control and FDI solutions, can reside in one platform, which could be a computation intensive DSP (Digital Signal Processor) based fieldbus type interfaces and standards [26].

1.2.7 FDI techniques: The general FDI methods are either model based or model free methods. Significant research activities concerning the model based fault detection methods are underway around the world. In the model based method we compare the analytically generated signals with the physically generated signals to decide the fault attributes [27-30]. Model based fault detection is performed in two stages, residual generation and fault isolation. A residual is the difference between the measurement derived signal and its model derived counterpart. The ideal residual will be zero when the system is healthy and non zero when there is a fault in the system. But this has a limitation. Because of the model error even if the system is healthy, the residual will be non zero. So, to confirm whether the residual fluctuations are due to model error or due to fault in the system, sophisticated isolation process is used [31]. Traditionally, residuals are generated in three standard ways: parity relations, observers, and spectral analysis. Isolation is achieved by using threshold or other statistical tests. More advanced techniques use adaptive threshold, and soft computing tools and techniques [32]. In spectral analysis method by tracking the amplitude and frequency distribution of measured signals and by comparing these with the characteristic of healthy system's signals one can detect the fault(s). Spectral analysis is done with the help of mathematical tools such as Fourier transform and wavelet transform [33]. Moreover, Wavelet analysis is a rapid growing tool having many applications in feature estimation process [34].

1.2.8 Expert systems for diagnostics: FDI involves detection and diagnostics. Once the fault is identified, it must be isolated. Technically, isolation and diagnostics are synonyms. The top layer of diagnostics is called prognostics which are defined in terms of life cycle data acquisition (LCDA) [35]. Expert system helps more on detection side than isolation process. It is embodied in software. An expert system employs system age, operating conditions and fault statistics along with logical rules to detect faults. Expert systems are designed by experienced system operators who are well acquainted with system failure modes as well as the effects that each failure mode has on the system signals. An expert system is often used for fault diagnosis subsequent to model based fault detection [36]. In practice, it derives a set of if-then-else rules and an inference mechanism that searches through the rule-space to draw conclusions and for this the expert system requires prior knowledge or information. Expert systems are developed completely on expert knowledge or can be based on first principles. They have an inference engine, which is capable of giving conclusions or additional information to reach a conclusion. The disadvantages of expert systems are not easy to develop, provide ambiguous transparent reasoning, worst reasoning under uncertain condition, and can not provide explanations for the conclusion [37].

1.2.9 More on soft computing: Fault detection and isolation (FDI) concepts for dynamic systems have received more and more attention due to an increasing demand for higher performance as well as due to higher safety and reliability standards. In recent years there has been an increasing amount of research in developing neurofuzzy logic to control and automate mechatronics systems [38]. Of particular interest are reliability issues for highly nonlinear systems, a sub field of control systems engineering for which little standard theory or design techniques exist. Fuzzy logic based solutions are now appearing on many consumer products, adding fuel to the decision problems [39]. From a theoretical point of view, such issues are robustness to uncertainties, variations, stability and signal degradation. FDI concepts basically consist of two major steps: the residual generation, i.e. the generation of a fault accentuated signal, and the residual evaluation, i.e. the evaluation of this signal by a certain logic. Different fault detection and isolation techniques have emerged over the last decade, most of which are based on knowledge of a system model. Given the success of fuzzy logic based real time control schemes, it is natural to investigate FDI from the neurofuzzy perspective as well [40].

1.3 Objective of the research

The objective of this research is to study appropriate schemes of Fault Detection and Isolation (FDI) for Mechatronic Systems. The objective was set taking into account of the fact that the research and development activities in this interdisciplinary field is not much.

1.3.1 Motivation: Mechatronic systems are a class of interdisciplinary engineering systems which entails greater reliability. Mechatronic design deals with the integrated design of an electomechanical system and its embedded control paradigm. This definition implies that it is important, as far as possible, that the system be designed as a whole. From the literature search, it is understood that the diagnostics and prognostics of mechatronics systems have become important due to demand in safety reliability, and productivity. This requires a system approach to the design problem. Since mechatronics is the synergistic integration of mechanical engineering with electronics and intelligent control algorithms in the design and manufacture of products process, the system by itself has multiple control targets called components . The control targets or components at the field-level are either sensor(s) and/or actuator(s). They are hard-wired and logically configured so that the control code along with stability algorithm will be executed in order to perform the desired task. Because, it is now possible to incorporate processing power at the field level with the rapid developments in embedded technology for improved programmability and flexibility, the use of PC, computing language and DSP platforms play a very important role in enabling a paradigm shift in reliability strategy. A device-level (sensor and actuator) framework for developing FDI schemes is adopted.

1.3.2 Findings: The two new FDI approaches such as (1) model-based feature estimation, and (2) multiresolution technique based approach are developed. FDI schemes are developed with chosen cases for actuator and sensor used in mechatronics systems. A proprietary electric motor based valve actuator, commonly used in pressure regulation applications (e.g., aircraft), was integrated and the developed FDI algorithm was tested and validated. Similarly, a simple transducer based sensor which has a wide use was selected to illustrate the multiresolution based FDI validation. Further, the driving behavior of a typical target application system such as an automated wheel chair is studied.

1.3.3 Methodology: In order to develop FDI algorithms, appropriate methodology and supporting tools such as model-based techniques, ANN, Fuzzy Logic, MATLAB, embedded technology (DSP boards), PC platforms, and GUI-based programming tools are used. These tools and systems are chosen because of their powerful architectural advantages, low-cost features, and adaptation to the objective of the research. In summary, the thesis includes literature search, methodology, formulation, framework, results, discussion, conclusion, and future directions which are presented in separate chapters in chronological order.

1.4 Roadmap to thesis

The thesis has been organized in seven chapters including introduction and conclusion. To provide a road map for the readers following the introduction chapter, an overview of the thesis is given below.

In the second chapter the literature review on Fault Detection and Isolation (FDI) concepts, principles for a class of engineering system particularly mechatronics systems has been discussed. The survey covers many aspects of FDI schemes such as statistical, model based and spectral analysis methods.

In the third chapter the fault detection and isolation methodologies are illustrated. These include the logical tools such as artificial neural network (ANN), fuzzy logic (FL) and physical tools such as MATLAB, Microsoft visual basic, DSP systems and boards, FPGA and personal computer (PC).

In the fourth chapter the various FDI schemes are validated through exemplar systems. The detail analysis of all the FDI schemes are presented

In the fifth chapter the modelling of physical mechatronic systems and devices are explained with two examples: (1) electric motor, (2) pneumatic actuating system. This chapter also demonstrates the modelling of wavelet transform and sensor output in the presence of fault.

Chapter 6 presents validation of different FDI schemes based on the result of some experimental studies which were conducted for model based feature estimation method and spectral analysis based multiresolution signal decomposition method.

The seventh chapter includes the conclusion part. In this chapter the research findings are summarized and the scope of future research is discussed.