An Epistemological Decision Making Framework for Fault Diagnosis

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Abstract— All systems known in nature can malfunction and fail due to faults in their components. Moreover, the growing complexity of industrial plants has also resulted in serious problems in process control which cannot be easily handled by operators. These abnormal events have significant economic and environmental impact. Thus, fault diagnosis has become increasingly important in recent years for the improvement of reliability, safety and efficiency of technical processes. This work attempts to make detailed investigations on Fault diagnosis for a Complex Benchmark Process Control System.

Keywords— Complex Systems, Epistemological Decision Making, Fault Diagnosis

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1 INTRODUCTION

NATURAL growth and technological advances have led to development of physical, biological and engineering systems with increasing size and functionality along with increasing demands on their performance. Hence, such systems have increased complexity and enhanced potential to fail, despite safe designs and improved quality control techniques .Thus, system failures have become unavoidable and a growing area of concern.

Further, the growing complexity of industrial plants, such as chemical, petrochemical, sugar and power etc, has also resulted in serious problems in process control which cannot be easily handled by operators. Industrial statistics show that about 70% of the industrial accidents are caused by human errors [1]. These abnormal events have significant economic and environmental impact. Thus, system failures are inevitable in today's complex industrial environment and there is apparent need for effective means of detecting them, due to their impact not only on the systems involved but on the society as a whole. As a result, there has been an increasing interest in fault diagnosis in recent years.

In industrial installations faults may occur in sensors, actuators, components of the controlled process, or within the hardware or/and software of automatic control systems. Moreover, faults in a component may develop into failure of the entire system. This situation can be handled by timely fault isolation followed by repair. Intelligent decision making for early diagnosis of faults is hence the first step to achieve effective automation. Therefore, it can be concluded that intelligent decision making has become the most important issue in operation and control of complex systems. During the last two and half decades, a large amount of research has been conducted in this field and a variety of methods have been proposed [2].

Early automation systems were based on a simple limit and trend value check. These were followed by the methods based on non-parametric signal analysis, e.g. autocorrelation functions, spectrum analysis etc. But these methods do not allow an in-depth fault diagnosis and do not simulate the human reasoning activity. Most of these methods require special sensors which increase costs and maintenance effort. Further, they require extensive experimentation and data acquisition, which is a difficult task in complex systems. Therefore, modern methods, which rely heavily on simulative analysis, have been developed in the recent years[3].

2 NEED FOR EPISTEMOLOGICAL DECISION-MAKING

The dominant paradigm for decision-making in any field is rational selection of a policy that achieves greatest preference within practical limits of time and resources. Thus, optimal control, optimal estimation, and optimal detection all stem from the common heritage of maximizing utility. When employing such a strategy, however, it must be assured that the criterion used for optimality is above controversy, and that there is sufficient modeling information available to operate the decision rule reliably.

Thus, the following two basic assumptions must be satisfied:-

- First, a best solution must exist.

- Second, there must be sufficient information, time, and resources to find it.

Meystel has named problems that meet these criteria "well-formed problems" [4]. Conversely, an ill-formed problem does not have a unique or well-defined notion of best, or insufficient information, time, or resources. The general knowledge based decision making system starts exhibiting a sudden performance degradation near or beyond the limits of its domain knowledge. Moreover, the decision making system is not able to generate satisfactory explanations, since it can only show the pragmatic constructs composing its own knowledge base. In addition, it may not solve novel problems that the designer did not anticipate while building the system, Finally, there may be several difficulties in acquiring and maintaining knowledge bases, because the systems need the heuristic insight of a domain expert more than mere domain knowledge.

Solutions for these problems may be achieved through a suitable design of the conceptual architecture before starting any implementation activity. This level of design is called knowledge level or epistemological level and the resulting system is epistemological decision making system.

These Challenges to decision making in ill-formed and complex systems make their operation and control extremely difficult. The limitations of decision making systems are further brought into the limelight when the plants they control or operate are susceptible to faults. In such cases the decisions may often go wrong or may be too late to prevent damage to the plant. Several new techniques in the area of computer based control have been developed and are being applied in the modern industrial plants. They are extremely efficient when dealing with a variety of operating conditions in the plant but often turn out to be severely limited in their scope when dealing with unforeseen and fault conditions, as is evident from the conversion of minor faults that are not properly catered into major catastrophes.

It is unfortunate that despite all advances in computer-based control of industrial plants, the fact that two of the worst ever chemical plant accidents [5], namely union carbide's gas tragedy at Bhopal, India and occidental petroleum's piper alpha accident have occurred and caused widespread loss of life and property. Another major incident is the explosion that occurred at the Kuwait Petrochemical's Mina Al-Ahmedi refinery in June 2000, which resulted in about 100 million dollars in damages. More recently, in November 2009 a major fire accident in Indian oil corporation fuel depot at Sitapura in Jaipur has resulted in an economic loss of about Rs 500 crore and in March 2011, fire in six nuclear reactors at Fukushima nuclear-power complexes in Japan after an earthquake have caused huge loss of life and property.

Further, industrial statistics have shown that even though major catastrophes and disasters from plant failures may be infrequent, minor accidents are very common, occurring on a day to day basis, resulting in many occupational injuries, illnesses and incurring large costs to the society every year [6]. It is estimated that the petrochemical industry alone in the US incurs approximately 20 billion dollars in annual losses due to poor abnormal event management [7]. The cost is much more when one includes similar situations in other industries such as pharmaceutical, specialty chemicals, power and so on. Similar accidents cost [8] the British economy up to 27 billion dollars every year and the Indian economy about 13.8 billion dollars every year.

Thus, prevention of catastrophic failures is the greatest challenge for control engineers. In the past, the regulatory control was automated using computers and thereby removing it from the hands of human operators. This has led to great progress in product quality and consistency, process safety and process efficiency. The current challenge is the automation of fault diagnosis and management using intelligent control systems, thereby providing human operators the assistance in this most pressing area of need. People in the process industries view this as the next major milestone in control systems research and application.

A sincere attempt has been made here to devise an appropriate technique for fault diagnosis of complex systems.

3 Desirable Characteristics of a Fault Diagnostic Classifier

Whenever an abnormality occurs in a process, a general diagnostic classifier would provide a set of hypotheses or faults that explains it. Thus, the desirable characteristics of a fault diagnostic classifier are:-

- Early detection and diagnosis
- Isolability
- Robustness
- Novelty indentifiability
- Multiple fault identification ability
- Explanation facility
- Adaptability
- Reasonable storage and computational requirement.

Completeness of a diagnostic classifier would require the actual fault(s) to be a subset of the proposed fault set. Resolution of a diagnostic classifier would require the fault set to be as minimal as possible. Thus, there is a trade-off between completeness , resolution and accuracy of predictions.

4 General Intelligent Control and Fault Diagnosis Framework

Figure 1 depicts the components of a general intelligent control and fault diagnosis framework. It shows a controlled process system and indicates the different sources of failures in it.

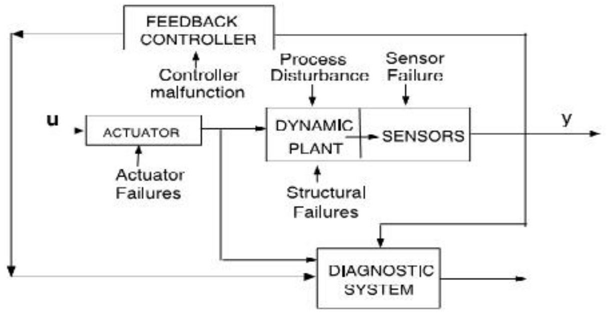

Figure 1: General Intelligent Control and Fault Diagnosis Framework [1]

In general, one has to deal with three classes of failures or malfunctions as described below:

4.1 Process Disturbances and Gross Parameter Changes in a Model

In any modeling, there are processes occurring below the selected level of detail of the model. These processes which are not modeled are typically lumped as parameters and these include interactions across the system boundary. Parameter failures arise when there is a disturbance entering the process from the environment through one or more exogenous (independent) variables.

4.2 Structural Changes

Structural changes refer to changes in the process itself. They occur due to hard failures in equipment. Structural malfunctions result in a change in the information flow between various variables. To handle such a failure in a diagnostic system would require the removal of the appropriate model equations and restructuring the other equations in order to describe the current situation of the process.

4.3 Malfunctioning Sensors, Controllers and Actuators

Errors usually occur with actuators, controllers and sensors due to a fixed failure, a constant bias (positive or negative) or an out-of range failure. A failure in one of the associated equipments could cause the plant state variables to deviate beyond acceptable limits unless the failure is detected promptly and corrective actions are accomplished in time. It is the purpose of diagnosis to quickly detect any equipment failure which could seriously degrade the performance of the control system.

5 Epistemological Decision-Making for Fault Diagnosis

Typically, a diagnostic problem starts with the observation of some behavior which is recognized as a deviation from the expected or desirable, i.e., a malfunction behavior or fault is observed. There are several dimensions of diagnostic strategies and information. The key idea is that the basic knowledge used and its organization leads to the strategies which can be employed. By focusing on different levels of knowledge representation or epistemological considerations, different diagnostic systems can be developed.

Since the task of diagnosis as a classification problem, the diagnostic system is also referred to as a diagnostic classifier. It is important to identify the various transformations that process measurements go through before the final diagnostic decision is made. In general, one can view the diagnostic decision-making process as a series of transformations or mappings on process measurements. Figure 2 shows the various transformations that process data go through during diagnosis.

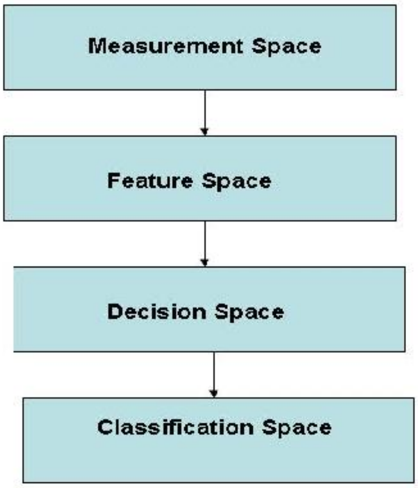

Figure 2: Transformations in a Diagnostic System

The measurement space is a space of measurements with no a priori problem knowledge relating these measurements. These are the inputs to the diagnostic system. The feature space is obtained as a function of the measurements by utilizing a priori problem knowledge. Here, the measurements are analyzed and combined using a priori process knowledge to extract useful features about the process behavior to aid diagnosis.

There are two ways of developing the feature space from the measurement space, namely,

- Feature selection and
- Feature extraction.

In feature selection, a few important measurements of the original measurement space are selected. Feature extraction is a procedure that facilitates, through the use of prior knowledge of the problem, a transformation of the measurement space into a space of fewer dimensions. For example, if a relationship is known to exist between the samples of one measurement and the samples of another measurement, feature extraction is concerned with identifying this relationship to represent them with a single set of parameters.

The mapping from the feature space to decision space is usually designated to meet some objective function (such as minimizing the misclassification). This transformation is achieved by either using a discriminant function or in some cases using simple threshold functions. The decision space is obtained by suitable transformations of the feature space. The class space is a set of integers, indexing the failure classes to indicate their category. The classification space is thus the final interpretation of the diagnostic system. The transformations from decision space to classification space are performed using threshold functions, template matching or symbolic reasoning as the case may be.

6. Practical Application

A detailed field study of sugar production process was carried out as a part of this research to identify various factors that affect the quality of sugar, existing control methods and its effect on final product. A sample data sheet of Rajasthan State Ganganagar Sugar Mills Ltd., Sriganganagar (India) for the Cane Crushing Season 2010-11 has been studied [9]. On study of the production data, it may be observed that the percentage of unproductive time for the duration ranging from 06.01.2011 to 15.03.2011 is 20.9%. In all, 342 hours 55 minutes were lost due to Stoppages on account of various reasons, in which Mechanical and Electrical faults share major part of 235 hours. These stoppages not only cause production loss but also have a significant adverse effect on the quality of production of entire batch in progress. Thus, ultimately faults incur a huge monetary loss to the plant.

As the sugar plants are seasonal and operate for a limited period of 3 to 4 months in a year, the faults conditions and their duration become a cause of major concern. The complex nature of production process demands high level of expertise, intelligence and knowledge for diagnosing the possible faults and for improving the productivity and quality of final product.

In view of the analysis mentioned above, it can be concluded that sugar plants are a suitable example of complex systems and favorable for a case study. The research work here has focused on the fault diagnosis in evaporator section of a sugar plant due its direct relationship with the quality and quantity of the final product. The major source of faults in this section results from malfunctioning of electro-pneumatic actuators.

The sugar factory investigations have shown that electro-pneumatic actuators employed in evaporator section have sufficient complexity to warrant detailed diagnostic study. It suffers from a variety of faults ranging from abrupt loss of signals to incipient mechanical failures. The study has shown that by simultaneous monitoring of several actuators and conditions of system operation, it is feasible to develop powerful diagnosis and supervision tools for the overall process under investigation. The likelihood that actuator systems (e.g. control valves, servomotors, positioners) will malfunction is significant when these components are installed in harsh environments (e.g. with high temperature, humidity, pollution, chemical solvents, aggressive media, etc.).

The identification of the development of small or incipient faults before they become serious, has an important influence on the predicted lifetime of an industrial actuator. Valve faults causing process disturbance and shutdown are of major economic concern and can sometimes be an issue of safety and environmental pollution. Furthermore, when actuators do not function correctly, the final product quality is influenced. The monitoring of the development of incipient faults is therefore an issue not only for predicting maintenance schedules but also for monitoring the performance of the process under study. Thus, fault diagnosis of electro-pneumatic actuator in evaporator section of a sugar plant, is an appropriate example of complex, dynamic and nonlinear industrial problems.

Complex systems often demand distributed decision making at several stages. Therefore, it is aimed to develop a methodology which may help in fast decision making at preliminary level and accurate decision making at secondary level. Thus, the fault cases which can be detected by perception should be handled at abstraction phase of decision making (i.e. Primary Decision Making System) without much computational effort. The correctness of fault detection at primary stage is ascertained by a Secondary Decision Making System that can detect the erroneously unreported fault cases using trends. This double checking process is essential for ensuring the safety of the system by timely detection of the fault at the initial stage. Apart from separating normal operation from fault cases, it is desired that Secondary Decision Making System may further segregate the fault cases depending upon their nature i.e. faults whose symptoms manifest suddenly i.e., Abrupt Faults, or faults whose symptoms grow gradually i.e., Incipient Faults.

Further, it is desirable to develop a suitable methodology for Intra-Class separation of various types of abrupt and incipient faults. Since the thrust of this research work is to base the fault diagnosis decision on deep insight of the process, hence an attempt will be made to select and utilize the best possible epistemic tools and techniques for this purpose.

Finally, for arriving at rational decision; the decision making system should be able to perform epistemological evaluation of adopted policy on the basis of the results from earlier stages of fault diagnosis. On the basis of this evaluation, decision making system should be able to choose its existing policy or adopt alternative policy for decision making. By virtue of this continuous learning, the targeted decision making system will be self learning and intelligent, i.e., it will learn autonomously from real time experience and further fine tune the decision making system for the continuous improvement in results. The proposed methodology would be validated on benchmark problem and applied to real industrial data. A Graphic User Interface (GUI) developed in MATLAB® according to above methodology has been shown in Figure 3. It has options for receiving data both from the actual plant and the Simulink model.

In addition to providing complete Fault Diagnosis, this GUI can be used for fast modular decision making, when partial knowledge regarding the fault is available. Thus, if the fault class is already known, then the relevant module can be used directly for decision making. For example, in the abrupt fault case, decision making using Statistical, Machine Learning and Neural Network Approaches can be used directly.

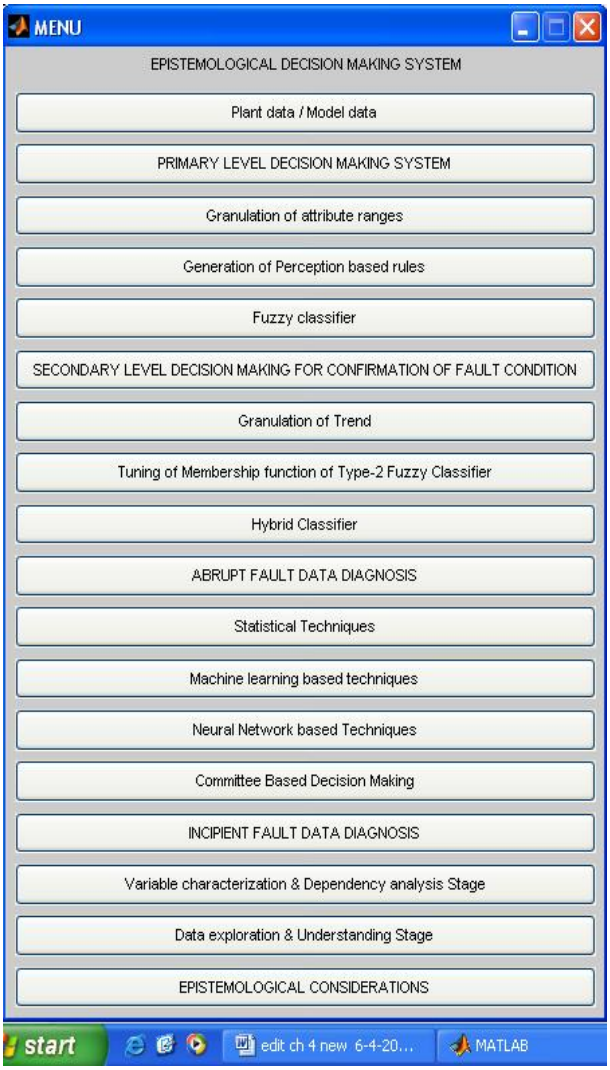

Figure 3: GUI Developed for Proposed Methodology

It is expected that the proposed methodology will overcome the limitations of conventional control methods for complex problems. The efficacy of the proposed methodology has been depicted by considering the problem of fault diagnosis in actuator employed in evaporator section of a sugar plant.

7 Conclusion

On taking holistic view it may be inferred that fault diagnosis involves epistemological decision-making process. Therefore, author has chosen to make detailed investigations on epistemological decision making for fault diagnosis for a complex benchmark process control system.

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