Real Time Fault Detection and Isolation: A Comparative Study

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ABSTRACT
Design and implementation of a complicated real-time system, completely free of fault is difficult and fault tolerance methods require features which are not usually follow the characteristics of a real-time systems. To deal with this issue, an appropriate automatic classification system to detect and diagnosis faults in run time should be utilized. This fault detection system must be independent of main real-time system and based on the received information it controls the behavior of real-time system. Type and content of this information has a main role to monitor and control real-time system and must be selected in such a way to determine the overall system status in normal and abnormal conditions. In this paper, after briefly discuss the major types of faults that can be happened in real-time systems , different methods of fault detention and isolation in real-time system are studied and evaluated.

Keywords
Real-time systems, Fault, Fault Detection, Fault Isolation.

1. INTRODUCTION
To detect, diagnose and correct classification, good understanding of system faults is required. For example to detect faults such as transient faults with different symptoms at different times, different control mechanisms should be applied.

In an intelligent real-time systems, lack of enough knowledge to decide about fault, causing uncertainty output response. Uncertainty is an important issue avoiding efficient decision and even causes inappropriate decisions that generate different type of faults. If these faults cannot be detected in an appropriate time may cause failure.[3,12] On the other hand, since the domain of occurrence and definition of intelligent real-time systems is wider than the other systems[13,14], it is needed to diagnose fault by efficient and high reliability methods using suitable monitoring system. However it is not a simple achievement because in addition to common faults, there are specific faults to create different responses and feedbacks. Sometimes monitoring system detects the fault and only in some cases may take steps to correct the faults. Beside this structure, the fault detection system must not create

overload for real-time system and not slowing system performance and raising other of faults.

The inability of complex systems at a specified time to avoid failure has two reasons. The first is lack of enough suitable sensors in the system during operation and the second is inability of human users for quick analysis of raw data from the sensors to determine status of implemented systems.

According to the importance of real-time intelligent systems in different areas of engineering sciences and their application in various fields in recent years, a deep survey on different methods of real time fault detection is required. In this paper after introduce the types of fault in section 2 ,the methods of fault detection and isolation in section 3 is classified and more describe in section5 , finally in section 8 these methods are compared in different aspect.

2. FAULT CLASSIFICATION IN INTELLIGENT REAL-TIME SYSTEMS
The main factors of failures in real time systems are classified in 4 groups: the first group is developer faults at the stage of problem definition and developing the system including accuracy in definition of algorithm, determining hardware and software and accuracy in system architecture. The second group is fault in implementing system that is transforming of the specification and design to real hardware and software. The third group of faults is Hardware failures and unplanned system failures that can be happened due to damage of components such as sensors, triggers and etc. The forth group is environment factors such as noise. The noise is an important factor in occurrence of faults like transient fault in the real time system. [5]

The scope of occurrence and definition of fault in intelligent real-time systems is wider and more complicated than other systems [5]. Some faults are occurred in all computer systems causing the failure in performance of system. These are software and hardware faults which are common among all computer systems.[8]

Other types of faults have no impact on performance of system but causing delay in system. As a result, a proper work is done after a specified time [24, 25]. These faults are contributed to common intelligent real-time systems [2, 14].Also, in these systems, there are new resources of faults due to lack of sufficient knowledge or weakness of programming language in translating problem solving knowledge into machine language which leads to uncertainty in the output response. According to the above, the existing fault and failure in these systems are more complicated than other computer systems [2, 3]. The faults in intelligent real-time systems are divided into three hardware faults, software faults and timing faults.

Hardware faults, specially are occurring in hardware and are divided into three groups: permanent, transient and periodic faults [12]. Permanent faults are occurred in hardware and will remain unless the defected component is changed .According to the type of hardware operation, sometimes or always or never are not lead to any defect. [17]Transient faults are occurred in a moment and will disappear immediately. This fault that is occurred in a brief moment, and possibly at the same time leads to the failure of system but after a few moments, the fault is disappeared that is common in digital system.[17]Periodic faults are occurred periodically in system and will be disappeared. These faults are caused by aging hardware and is the same in all systems .Software faults are caused by fault in logic algorithm due to developer faults in the design of algorithms and invalid inputs which are existed in the nature of algorithm logic or during implementation [14, 10]. Invalid and incorrect inputs can be the cause of the fault resources in software system. Moreover , insufficient and uncertainly in problem solving knowledge, the limitations of knowledge representation language and etc are the main causes of software faults in intelligent real-time systems. Timing faults cause delay in system and make the desired result is not achieved within the specific time. This fault may be due to environmental noises which have a negative impact on timing parameters and causing delay in performance of system and increase response time of system.[9,5]

3. DETECTION, DIAGNOSIS AND CLASSIFICATION OF FAULTS IN REAL-TIME SYSTEMS

Many researches have been done on real-time systems and as limited, on intelligent real-time systems to innovate methods in order to guarantee the good performance and timing constraints [4, 25]. Despite, achieve to this purpose, for two main reasons seem very difficult. The first is that, these intelligent real-time systems are depends on external environment ,so the performance of them depends on external environment. Since, predict the behavior of external environment is not possible, the behavior of these systems is not predictable. The second reason is faults or errors which may be existed in design of intelligent real-time system. In fact, due to specific condition in these systems, ability to fault diagnostic and check the all state of system status was very complicated and causing faults in the design process of intelligent real-time systems [23,26]. The above reasons allow researchers to suggest methods for detection, diagnosis and classification of fault in order to control intelligent real-time behavior of system which are divided into 3 groups. [3, 5] a) Software monitor: In these methods, software is located beside intelligent real time systems to monitor it .b) Hardware monitor: A separate hardware is installed beside the system to monitor it .c) Combined methods: Is composed of a software and hardware .Generally, three purposes must be considered in monitors design. [2, 5]1-Monitor must be separated from real-time intelligent system and have the minimum relation with it.2-Having the minimum delay in fault detection. In sensitive real-time intelligent systems, after occurring fault, the relating reaction must be done by a specified time.3-Overload due to monitoring system must be minimum, because the excessive delay of monitor on common source causing delay in real-time intelligent systems and the risk of delay increases. The most common method for detection, diagnosis and classification of fault and monitoring it in real-time intelligent system is using software to store, examine and analyzing specified behavior of real-time intelligent system and different fault detection. This process has two phases: The first is understanding event and includes detection the behavior of events during program execution implemented by software interrupts or entering commands in the code of real-time intelligent system program. In second phase that is called submit an event, information relating to event is gathered and stored based on predefined structure. Through this information the behavior of real-time intelligent system can be described. In case of how to use monitor information, the process of detection, diagnosis and classification is performed in two different levels:

[5, 2]1- Process level: The events in this level are relating to process behavior, their relationship with each other and with operating system .For example relationship between processes and exchange of information on synchronicity.

2- Functions level: The events occurring in function of process and among functions. For example, calling a function with other functions and variables return introduced in this level .Finally, each monitoring system generally consist of 4 subsystems and its operation is presented in 4 processes:1-Automation observation system 2-Fault detection system 3-Fault diagnostic system 4-Prediction system. [2, 21, 25]. There are two subsystems such as fault detection and fault diagnostic that control processes and environments permanently. Next step is evaluating fault that its purpose is detecting importance, status and the impact of fault on system performance to evaluate parameters such as cost, energy and etc. In final process, Faults must be corrected in order to reduce damage to system. In other words, system must present a proper response to deal with the occurred faults. [5, 27]

In figure 1, the relationship between the terminologies used in the domain of this article applied in references is depicted. The prevalence of key and repeated words is shown in the form of a graph that its nodes show terms and the edges show the relationship between terms and frequency of their applications. This abundance is marked with numbered circles located on repeated edges. Since , this diagram is provided based on 50 resources and on the other hand, these resources have applied real-time system in different areas , so , application of the terminology associated with real-time systems are seen in most of areas and as a result , talk about real-time fault detection is very important . Other terms used in this area are systems based on knowledge which as mentioned in section 5.2, different methods are used for fault detection.

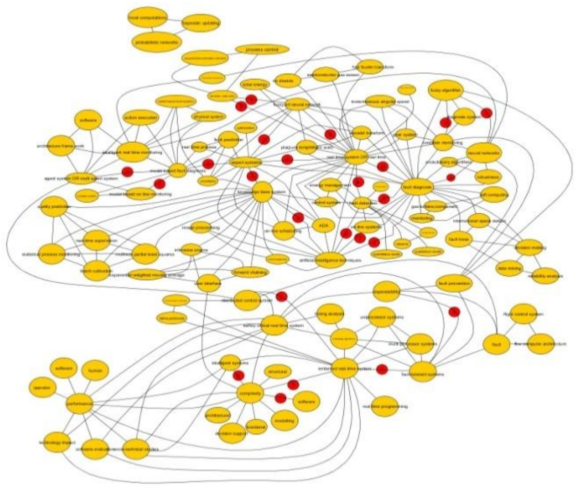

Figure 1: Real-time fault detection taxonomy diagram .

4. QOS DEFINITIONS

Generally to evaluate Fault detection procedures in real-time intelligent systems, there are qualitative and quantitative metric which are depending on specification of problem domain. So, to evaluate methods applied through quantitative method in papers, different metrics are applied and method compare criterion most have been based on qualitative metric. However, to confirm more excellent method, quantitative criterion comparison is considered. There are different methods in dealing with faults: State-based approach: In this method, diagnosis by verified system state at any time is calculated regardless of system behavior over time. Simulation-based approach: In this method, diagnosis is relying on temporary behavior of the system, how the system passes from one state to the next is calculated. Compile-based approach: In this method, model of a system includes temporary behavior of system. Before the online diagnosis is begun, it is compiled as off-line. [2, 10]

To determine excellent criterions in terms of quantitative and qualitative, they must be separated. Model-based methods are divided into two quantitative and qualitative groups. [50, 30]Quantitative model methods apply mathematic models based on physical principles to model system. To achieve this purpose, the relationship between system variables and their mathematic model should be specified. By applying physical rules to describe system, differential equations relating to system process model and estimate system response according to appropriate inputs and compare them with real output of system can be achieved . Criterions such as: Estimated time to occurrence of fault conditions and failure states, the number of false diagnostic alarms, the time delay in detecting faults, diagnostic faults size, the accuracy of the measurement, the percentage of fault detection. Unlike quantitative modeling techniques, qualitative models use qualitative relations or knowledge base to analyze system and fault diagnostic. This means methods base on qualitative model use the result of qualitative relationships obtained from physical knowledge to model the system; meanwhile, a number of qualitative methods are obtained by the past inference of the data process. In contrast the above methods that use the previous qualitative and quantitative knowledge for modeling system ,there is the third method that is based on data-based modeling [50]. In this method, system behavior is modeled based on stored data in data base, applying statistical methods, decision tree, neural network and etc. The main purpose of this method is linking the input and output through mathematical rules. In these systems, qualitative criterions are used for comparison, criterions such as: initial fault detection, multi -fault detection, output response justification, compatibility, uncertainty control, real-time calculations requirements and reliability.

5. DETECTION METHODS AND FAULT ASSESSMENT IN REAL-TIME SYSTEMS

Soft computing techniques, such as expert systems, neural networks, fuzzy logic, genetic algorithms, decision trees and bayesian network are used as fault detection techniques in fault detection and isolation system. The techniques for fault detection, deal with interpretation of signals ,sensor's control signals ,discover the unusual items and modes , produce and creating hypotheses about the behavior of faults and their description. [28, 1]

However, applying these methods solves a part of problems, but there are some difficulties. In this paper, presenting a comprehensive classification for real-time methods of fault detection in real time systems is tried.

5.1 Classification of methods

To classify different methods of fault detection, there are different criterions. From one perspective methods can be classified base on knowledge or soft computing, with this point of view expert systems in the first category and other methods such as neural networks, fuzzy logic, genetic algorithms and combinational methods are placed in the second category. Since, fault detection in expert systems follows a heuristic process; this process is created based on rule- based methods. About genetic algorithm, since their nature is in such a way that not include in complicated system performance, so not examined. Fuzzy and bayesian systems in terms of how to deal with uncertainty are included in both groups.

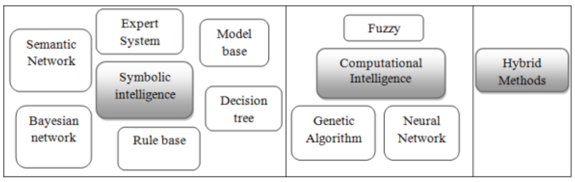

Figure 2 :Classification of real-time fault detection methods.

5.2 Knowledge –based systems (symbolic intelligence)

In these systems, system knowledge is separated from software controlling its application. In the simplest state, these systems are composed of two components: knowledge base and inference mechanism.

Separating knowledge from control, make easier to gain new knowledge during the development of the program or even after gaining experience during the program. This feature for real-time intelligent systems means that , if the arrangement of system changes or new regulations imposed on them , knowledge base can be updated without need to amend the inference mechanism, while common programming method is used, total program needs to be amended due to integration of knowledge and inference mechanism[2,3]. Another useful characteristic of knowledge-based systems is the ability of justification for conclusions and also reasoning them that is important for understanding of human user. Model-based systems, rule-based systems, decision tree, bayesian network, semantic network and fuzzy logic are examples of this system applied for fault detection, decision support in monitoring systems that are evaluated in following.

5.2.1 Model-based systems

These systems are based on cause and effect relationships. The model detection task is that when it received an abnormal behavior, it must specify that which fault is occurring. This work is done based on probability selection. Generally, there are three potential applications for model-based systems:1-System monitors for observation and verify processes2-Finding a suspicious component and a preliminary diagnosis3-Confirmation or re-preparation of preliminary diagnosis by simulation. Model-based systems advantages include:1-A model to maintain, has lower cost than a rule base. Changes of real monde can be reflected in model changes easily. 2-Since sensors are treated like other components and a defect sensor can be obvious like other faults, this model doesn't need to search for verifying sensor status.3-Separation duty of all parts4-Model can simulate a physical system in order to detect, diagnose, classify or examine a hypothesis. Using model-based systems in real-time system , even if a complete and exact model is exist, it has this disadvantage that it only will work in a linear and simple condition, while real-time systems has a dynamic and non-linear nature.[30]

5.2.2 Rule-based systems

A rule-based system is based on knowledge that its knowledge base is presented in a form of a set of rules [29]. The simplest type of rule is based on " if then condition" relation, but this system does not have acceptable performance in some cases. Three reasons for non-performance of rule-based diagnosis include [29, 21]:1-Uncertainties due to gathered data or self-modeling, so extracting direct results by help of rule is associated with misleading results.

2-To create a full set of rule, for any possible fault, an expert person or knowledge engineer must predict a set of symptoms. This information may not be available because of faults that have never happened. 3-Effects are obtained through reading sensors and a large number of rules to detect a fault alone is needed to verify sensor data for solidarity.4-Since, a set of rules can be developed suddenly, it can be obsolete immediately. Also, due to interdependence, updating rule base need to think more than new rule that can be easily done. In addition, expressing uncertain knowledge in rule-based knowledge base is very difficult.

5.2.3 Semantic network

This method is appropriate for small environments, information are presented as a set of nodes connected by labeled branches. To achieve this purpose, a directed graph is used. Each node introducing a concept or an object and each edge introducing a relationship between two nodes. Information which are significant for inference mechanism, in this network is (IS-a) and also has an inheritance relations. According to the limitations of graph, semantic network has the same limitations. Semantic network expresses a part of descriptive knowledge that has and certain knowledge .also this language explains a method to present knowledge about objects and their relationships. Data are reasoned in semantic network to create systems equipped with knowledge about that specific area.[31]

The main advantage of semantic network in diagnosis process is its simple expression but also the restriction versus are as follow:1-Existing relation in semantic network graph having certain knowledge as a descriptive and binary relation and an edge only connects two nodes and uncertain knowledge causing lack of relation. Lack of support in uncertain knowledge is considered as a limitation of this method in real-time systems. 2-The next problem in semantic network is inability in presenting n-array relation ,To remove this defect the n-array relation must be converted to n binary relationship.3- Multiple inheritance relationship is another problem in semantic network. Whenever these features don't violate each other, multiple heritance is allowed. The best method to deal with this problem is predicting it while creating knowledge base and direct allocation of features to concepts while creating knowledge base.

5.2.4 Decision tree

Complicated systems usually use fault tree for analyzing faults. Analysis of fault tree considers possible causes of incorrect system performance and show suspected components of fault and faulty related modes [31]. Diagnosis and decision is performed by expert individuals and not automatically. To automate this process, decision tree can be used. Through this method, the concepts of fault tree are achieved and this algorithm is applied for online diagnosis of faults. In this way, knowledge and fault detection is shown as fault diagnosis rule. This tree is called fault tree. By moving from root to leaf, occurred fault can be diagnosed. Through this method, A real-time intelligent faults detection systems can be achieved.

There are two types of fault tree: fixed decision fault tree created based on fault tree and dynamic decision fault tree created by data in a specific time. This tree can diagnose unknown faults.

5.2.5 Bayesian network

Bayesian network is innovated by Tomas Bayesian. This technique is based on knowledge to diagnose faults or failures existed in different systems such as real-time systems. The Bayesian network is based on Bayesian rules in the conditional probabilities engineering, but its application is based on cause and effect. So any fault occurred in real-time system, has a main cause. A Bayesian network is composed of controlled acyclic graph and the conditional probability table. This diagram is created by variable nodes and directed connections which show relationship between variables. Conditional probability tables of each variable quantity the relationship between variables [34]. The advantages of this network in fault detection in complex operation of real-time intelligent systems are expressed in brief as following:

1-A Bayesian network creates reasoning by considering uncertainty through an approved and strong possible case, so, Bayesian network facilitates analysis of fault detection in operation or performance of real-time intelligent systems .

2-Bayesian network emphasizes on relationship between the nature of physical systems and it can simulate physical system behavior on model-based systems.

3-If there is enough information for model, Bayesian network can identify the root cause of fault or mistake with high reliability. If available information is not enough, many estimated analysis is provided.

4-new symptoms or relationship can be added to model easily without coercion of identify entire model. However Bayesian network is very power full in relationships of cause and effect and fault detection, but there are two main defects while employing in complicated real-time systems:

First, the size of knowledge base in case of system exponentially growth is associated with complexity. This complexity reduces conclusions and its real-time ability. By increasing the number of sensors in order to increase of accuracy and enrichment of knowledge base, massive amounts of data are received with the help of monitoring system. This massive data doesn't allow the system to support specific real-time features.

Secondly, when the system is greater and more complex, need for calculations are increased. It seems, these are most important factors that have reduced the practical performance of system.

5.2.6 Detection, diagnosis and classification system based on expert system

The first expert system for fault diagnosis for technical fault diagnostic was created in early years of 1970 in MIT University. Since then, many expert systems were designed and implemented [3, 35]. Early fault detection expert systems are rule-based and use experimental reasoning. Limitations of expert systems are expressed as following [35, 36]:

1-The inability to display, presentation and correct expression of multi-timing and complex phenomena

2-Knowledge Engineering difficult to gain knowledge from experts

3-Knowledge Engineering difficult to ensure consistency in the knowledge base

4-System inability in learning faults (understanding and identification).

Rule-based approach has several weaknesses such as lack of generality, universality and lack of mobility in new status. The next expert systems are based on model and uses duty reasoning [32]. Fault detection real-time expert systems are considered as new research areas created by combination of quantitative and qualitative fault diagnostic methods. This combination makes possible analysis of information and knowledge about fault diagnostic system.

One of the most important characteristics of on-line real-time system is that, in addition to previous knowledge base, there is a knowledge base including all information about the current state of monitoring system. This information are received online from sensors. Knowledge base is changing and improving permanently. Response time is a topic and critical events for online expert systems and is very important. So, calculations and fault diagnostic must be done in a specified time to detect and control fault on suitable time .expert system includes interfaces with the external environment for internal data collection. Whenever data have a low validity due to instability and variability of time or sensor performance, system must identify it and process data correctly. however knowledge-based techniques are appropriate for calculations and symbolic processes , but numerical calculations has a main role in supplying and providing a part of information for decision making that are not presented in this study .

6. COMPUTATIONAL INTELLIGENCE

Computational intelligence in introducing knowledge is known as a part of soft computational methods including neural networks, genetic algorithm and other optimization techniques. Fuzzy logic and Bayesian systems to deal with uncertainty are included in both knowledge-based system and computational intelligence [1, 3]

Genetic algorithm and other the same optimization algorithm are not included in fault detection methods and prediction in complex systems. In other word, neural networks for classification, non-linear estimation and etc are used. So, neural networks are more appropriate than optimized algorithms for implementing in intelligent detection, diagnosis and classification systems. So, in this section, neural network techniques are expressed briefly [1, 3].

6.1 Neural networks

Artificial neural networks are composed of computing non-linear components which are network nodes or neural neurons. Neural networks provide a useful technique for determining variables that not measured easily. Measurable variables identify network entrance and output unknown variables [6]. In the range of intelligent real-time system performance, this matter means that, measurable variables of numbers are read by sensors and unknown variables show status of suitable components in detection, diagnosis and classification system. This method is practical and useful early fault detections[3].

The ability of these networks is learning previous system data to model it. Neural network models need only basic information about physical characteristics of systems. Neural networks are used for fault detection and fault diagnostic for two purpose: 1-modelling system 2-classification that presented in articles as three modes [35]. In the first method, neural network is applied to classify normal and abnormal condition by using system process output. Learning neural network can perform on-line or off-line. In the second method, neural network applies a classifieds to separate faults relating to the difference between process output and process model, And Process model can be qualitative or quantitative. In the third method, a neural network applied to model process and classifieds.

Using neural network techniques in detection, diagnosis and classification system show two main advantages:

1-Neural network is able to produce an approximate solution even by receiving incomplete or distorted data.

2-Any neural neuron implements its calculations independent of other neural neurons except that, outputs of some neural neurons may compose inputs for other neurons. Neural networks have a high parallel structure to discover many fault resources simultaneously. This parallelism enables neural networks to use parallel processing computers.

There are two major drawbacks in neural networks:

1-Performance domain of intelligent real time systems needs good understanding of users about events and their causes. Inputs and outputs of the neural network are visible to users but weights in the relationship between the intermediate layer is uncertain. This obscurity is not able to specify system logic and also, neural network is not able to describe reasons logically.

2-To achieve neural network models with reliability and high accuracy in complex system such as real-time intelligent systems, neural network requires to be educated by a massive amounts of input and output data. In complex systems, previous data have not enough detail about faults and their symptoms. So, design of neural networks for detection, diagnosis and classification systems through available data is very difficult. Accordingly , neural networks are not able to explain logic and instructions, then , proving the accuracy of results is very difficult , because ,on many issues , balanced weights are not interpretable so the logic hidden behind decision is not clear . Neural network computing needs high amount of data for training and testing model. In general, neural networks have no efficiency for some problems, for example, artificial neural network is not appropriate to solve problems and processing data by reasoning method [1, 35].

6.2 Fuzzy logic

Mr. Lotfi presented fuzzy logic [32]. This theory is a method to administrate uncertainty due to the ambiguity of language. Fuzzy modeling is a method to model non-linear and uncertain systems. Modeling system by fuzzy method is based on our understanding of system behavior and base on rules. These rules and membership degree functions in fuzzy systems can model non-linear behaviors of system very well. Also, fuzzy model can be created by the data. These techniques will facilitate the extraction of knowledge from the expert problem domain [33]. The fault occurred in system shows the difference between estimated output signal by a system model and real output signal that must be evaluated. this difference can be expressed by Language variables in fuzzy logic .so the difference can be evaluated by inferring these variables and rule base ,As a result evaluation of fault, is a logic decision process converts quantitative knowledge to qualitative terms [33]. This conversion is performed by fuzzy concepts in three phases:

1-checking remaining signs 2-fuzzification 3- Inference and finally defuzzification

Fuzzy logic is applied in different parts of a detection, diagnosis and classification system. In the first step, a system process can be modeled by the above method as qualitatively. Also, to express uncertainty, differences are evaluated by fuzzy logic and present by language variables. Finally, the existing knowledge of occurred fault system is classified through these differences and fuzzy inference [33].

Uncertainty fuzzy sets are expressed by introducing behavioral membership functions whose values are between 0, 1 according to membership degree from ‘non-member ‘to ' full member ‘. Fuzzy logic systems having the most rules –based defects of systems, however it is trying to solve uncertainty in knowledge [32].

7. HYBRID METHODS

In this method, a combination of each mentioned methods for identification and fault detection is used

8. COMPARE METHODS

As mentioned above, in section 4, the studied methods are classified in qualitative and data models. So, their comparison in terms of qualitative criterions is more common than quantitative factors. The following table presents a qualitative comparison of the methods that expressed in the previous sections:

Table 1: Comparison of real-time fault detection methods

Comparison criterion(qualitative parameters)	Model-based System	Rule-based System	Semantic Network	Decision Tree	Fuzzy Logic	Bayesian Networks	Neural Network
Initial fault detection	Yes	No	No	Yes	Yes	Yes	Yes
Multi-fault detection	Yes	No	No	No	No	Yes	No
Control of uncertainty	No	No	No	Yes	Yes	Yes	No
Compatibility	No	No	No	Yes	No	Yes	Yes
Real-time computing requirements	No	yes	yes	No	No	No	yes
Output response justification	Yes	Yes	Yes	No	Yes	Yes	No

9. CONCLUSION

In this paper, detection, diagnosis and classification methods of real-time fault detection were evaluated. Since, identifying the behavior and the proper functioning of real-time intelligent systems to deal with faults is very important. It is needed to present a comprehensive research in this field to understand experiences and architectures provided by researchers in different studies. Despite the extent topic of faults and its detection in engineering fields, still, a general method has not been presented for adding the capability of detection, diagnosis and classification of fault in real time system. Although some researches have presented specific solutions.

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