# Ontology-based Fault Diagnosis: A Decade in Review

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## ABSTRACT
Fault diagnosis is a critical activity in the comprehensive support for equipment operation. Relevant research about it is becoming more and more popular. Ontology-based fault diagnosis is an important method for diagnosing faults. Due to the expressive ability, knowledge sharing and knowledge reuse based on deep semantics, and the support of logical reasoning, ontology-based fault diagnosis has received more and more attention from researchers in the past decade. The fault diagnosis ontology describes the core concepts involved in diagnosing faults and the relationship among the concepts. Its quality and usage determine the efficiency and effectiveness of fault diagnosis, thus has a great impact on fault diagnosis. This paper investigates and analyzes the research work of ontology-based fault diagnosis in the past decade, from the perspective of knowledge source and usage of fault diagnosis ontology. The current research states are summarized, challenges are pointed out, solutions to these challenges are discussed and trends of related research are tried to be grasped.

## CCS Concepts
• **Artificial intelligence→Knowledge representation and reasoning→Knowledge engineering.**

## Keywords
Fault diagnosis; Knowledge-based system; Ontology.

## 1. INTRODUCTION
With the rapid economic and industrial progress, human society has entered an intelligent era, and the automation of various industries is rapidly advancing. The automation system generates a large number of faults and their related data. A fault (also named failure sometimes) is the case which certain characteristics or parameters of the system deviate from normal values, so that the system cannot operate normally with deteriorated performances and even disasters occur [3; 24]. Fault diagnosis plays a key role in ensuring the normal operations of equipments. It can greatly extend the serving life of equipments, improve production efficiency and reduce production costs [33]. Fault diagnosis makes judgments on the operating status and abnormal conditions of the system, and provides a basis for system fault recovery. The three subtasks are fault detection, fault isolation and fault identification [10; 29].

More and more faults are generated by the automation system, making the need for fault diagnosis more and more urgent in industry. There has been more and more research on fault diagnosis from the academic community. Especially, the research on fault diagnosis has been increasing year by year in general since the 21st century. For example, the number of papers containing "fault diagnosis" included in the Web of Science (WOS) database each year from 2000 to 2018 are reported in Figure 1 (obtained by literature analysis using Clarivate Analytics for Jan/1/2000 ~ Oct/1/2018).

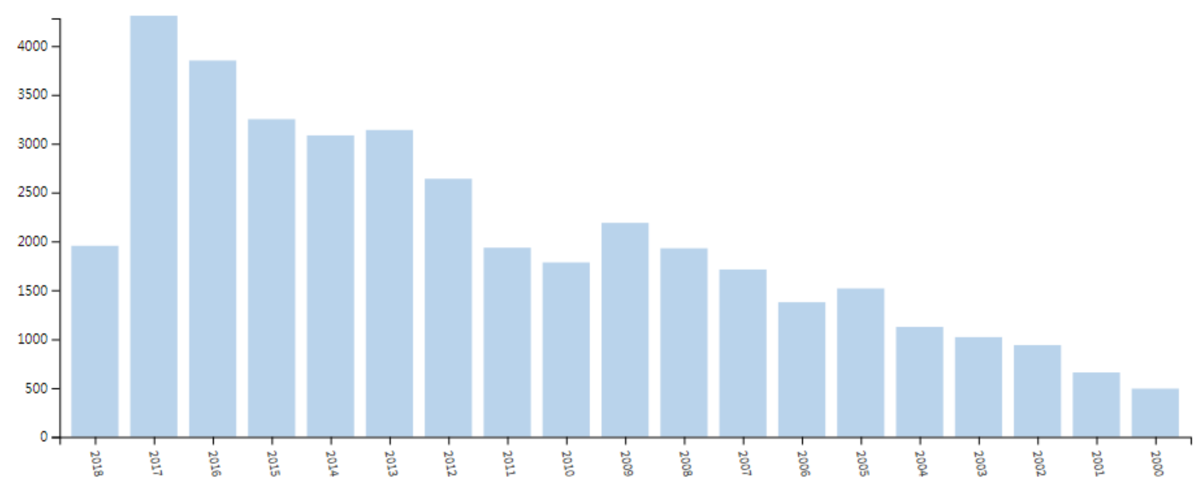
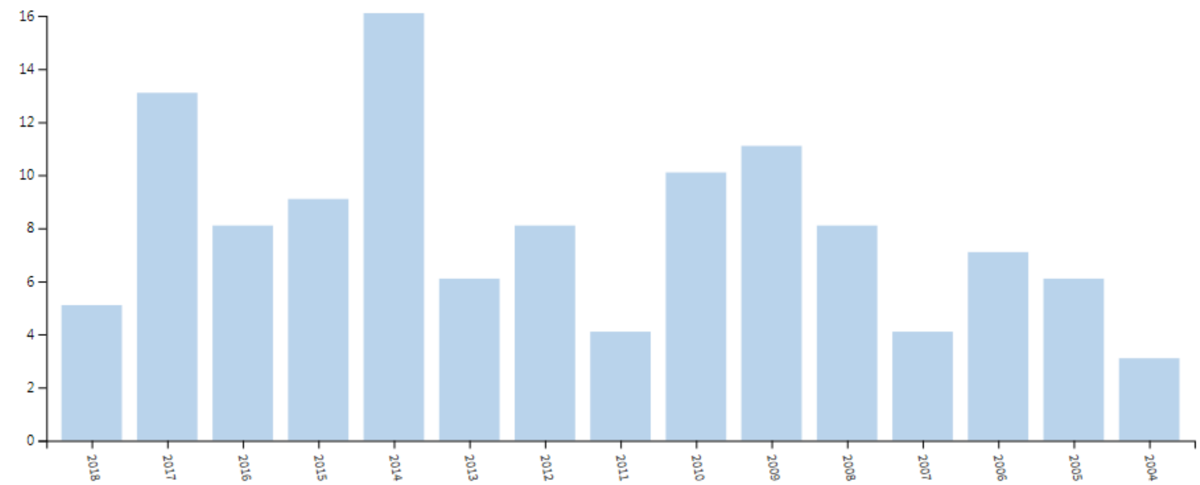



**Figure 1. Number of papers related to "fault diagnosis" included in WOS each year after 2000.**

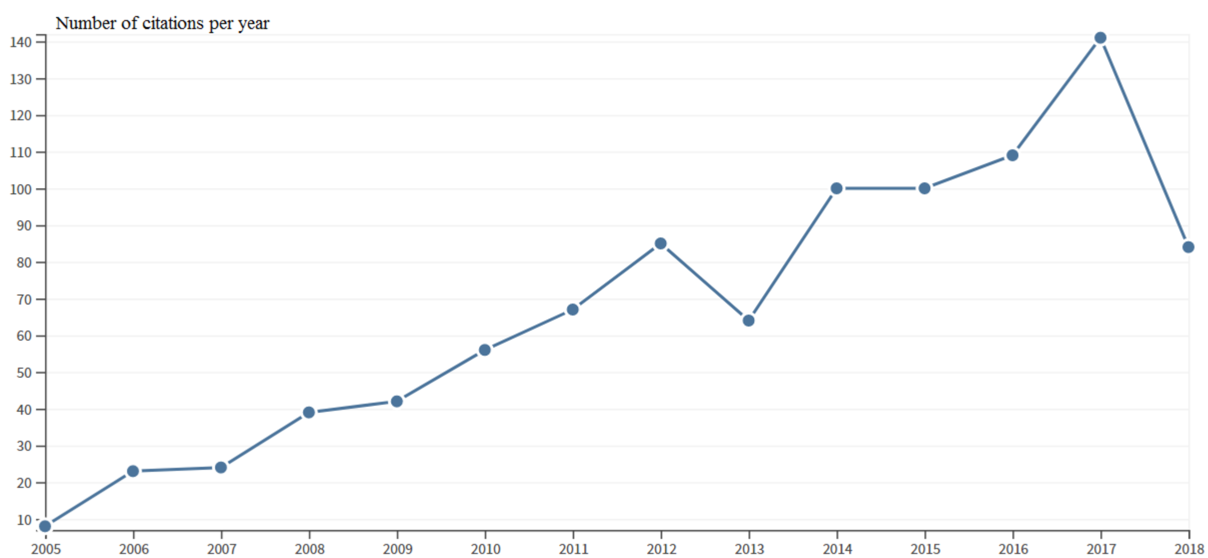
In Figure 1, the horizontal axis represents the year, and the vertical axis is the number of papers included in the WOS database each year. It can be seen from Figure 1 that the published literature on fault diagnosis has been growing strongly in most years since 2000. In particular, the number of papers published in the past decade is not less than 1,800, indicating that fault diagnosis is a hot research topic. As the hotspots in the academic community and industry, fault diagnosis methods and applications have received extensive attentions, and research about fault diagnosis endures.

Fault diagnosis methods can be divided into 3 categories: model-based methods, signal processing-based methods, and knowledge-based methods [8; 10; 11]. With the development of computer technology and artificial intelligence, the fault diagnosis with signal detection and processing as its core task gradually transits to the fault diagnosis with knowledge processing as the core task [4; 33]. The knowledge-based fault diagnosis method deploys a variety of artificial intelligence techniques [11]. It is also known as intelligent fault diagnosis [34]. The intelligent fault diagnosis systems are mainly divided into three categories: expert systems, data-driven systems, and ontology-based systems [33].

Ontology is a kind of knowledge representation technology with expressiveness of strong ability and high efficiency. It facilitates knowledge sharing and knowledge reuse based on deep semantics and supports logical reasoning. For theses reasons, it is widely used in intelligent fault diagnosis [4; 6; 27; 34]. In particular during the past decade, ontology-based fault diagnosis has received more and more attention from researchers. For example, the number of papers containing "fault diagnosis + ontology" included in the WOS database and numbers of their citations each year from 2000 to 2018 are reported in Figure 2 (obtained by literature analysis using Clarivate Analytics for Jan/1/2000 ~ Oct/1/2018).




(a)Number of papers related to “fault diagnosis + ontology” included in WOS each year after 2000




(b)Number of citations per year in the WOS database on “fault diagnosis + ontology”

**Figure 2. Searching for the results of literature analysis of "fault diagnosis + ontology" in the WOS database.**

As can be seen from Figure 2(a), WOS has been including literature on ontology and fault diagnosis since 2004. At least 5 papers have been included each year in the past decade, indicating that ontology-based intelligent fault diagnosis has made some progress. It can be seen Figure 2(b) that in the past 15 years, the number of citations in the WOS database about “fault diagnosis + ontology” is increasing year by year. Especially, in the past decade the number of citations is more than 40 per year, indicating that the research results on ontology and fault diagnosis are paid more and more attention to, studied and approved by researchers.

In the ontology-based fault diagnosis method, ontology describes the core concepts involved in diagnosing faults and the relationship among the concepts. As the knowledge base of fault diagnosis, the fault diagnosis ontology determines the efficiency and effects of fault diagnosis according to its quality and usage, thus is the foundation of ontology-based fault diagnosis. This paper examines the ontology research used for fault diagnosis over the past decade, from the perspective of knowledge source and usage of fault diagnosis ontology. We summarizes and analyzes the current research situation, points out the current challenges, discusses the solutions to these challenges and tries to grasp the development trend of related research.

# 2. KNOWLEDGE SOURCES FOR FAULT DIAGNOSIS ONTOLOGY

Currently, there are two main types of knowledge represented by fault diagnosis ontology: Failure Mode, Effect and criticality Analysis (FMECA) and the structural characteristics of the diagnostic object. FMECA is the experience of reliability analysis obtained during the period of product design. It includes Failure Mode and Effect Analysis (FMEA) and Criticality Analysis (CA) [15]. The structural characteristics of the diagnostic object mainly describe concepts about components and context of the diagnostic object and their technical parameters, and the relationships among these concepts [17; 18].

## 2.1 Knowledge From FMECA

FMECA describes the basic concepts of fault diagnosis, including fault mode (also called fault symptoms [21; 22] or fault phenomena [14; 34]), fault causes, fault effects and criticality analysis (also called severity in FMECA report). These basic concepts are in general named as fault element [34]. By analyzing the table of FMECA report, the basic concepts involved in fault diagnosis and the relationship among these concepts can be clarified. Based on this operation, the fault diagnosis ontology is used to represent concepts such as fault mode, fault effect, fault cause, severity and their relationships.

In the fault diagnosis ontology, the properties describing relationships between concepts and the concepts about features are used to describe or define the fault elements. For example, failure modes can be described by key characteristics of the diagnostic object [23], and fault elements can be defined by the essential attributes [34]. By analyzing FMECA, it can be seen that the fault effect is generated by the fault mode, thus, the concept *Fault Effect* can be associated with the concept *Fault Mode* using a relationship named *effectOf* [23; 31]; the fault mode is caused by the fault cause, hence, the relationship named *causedBy* can be used to establish a connection between the concept *Fault Cause* and *Fault Mode* [14; 31; 34]; in some domains of fault diagnosis, the fault cause and the fault effect are considered as subclasses of the fault mode [28; 31]; the repair recommendations are derived from the fault cause, thus there is also a need to establish a link between these two concepts [14].

The relationships between fault modes and fault causes, fault causes and repair suggestions are not always one-to-one relationships, because the real world is so complex and variable. Therefore, it is difficult for the FMECA report table to cover all possible situations completely. All in all, the completeness of the knowledge in fault diagnosis ontology needs to be improved further through other approaches such as data mining and drawing knowledge from other sources.

## 2.2 Object Structural Characteristics

In fault diagnosis, the diagnostic object sometimes consists of several subsystems, and each subsystem is composed of several sub-assemblies further. For example, the power source subsystem of a satellite is composed of several sub-assemblies such as primary power supply subsystem and overall circuit subsystem [14], and a fleet's subsystems are ships [17]. To give the repair or maintenance proposal, the fault causes need to be determined at first. Fault causes are designed defects that cause the fault modes, and their granularities are determined by the smallest replaceable parts in maintenance [23]. Fault causes are also considered to be the locations where faults happen at, i.e., the components of the diagnostic objects [17; 22; 23; 26]. Therefore, representing the structural characteristics of the diagnostic object by fault diagnosis ontology helps to find the fault causes and benefits generating repair or maintenance proposals.

The components of the diagnostic object are related to each other and interact with each other. Based on this fact, influence relationships between fault causes can be analyzed during fault diagnosis. Fault diagnosis ontology can describe the relationships among the components, such as connections [18], compositions (*partOf*) [23; 31], processing (*load*, *move*) [26], association [19], and so on. The description of the relationships among the components provides a basis for finding deeper root causes in fault diagnosis and is the basis for providing more accurate and precise proposals and recommendations for repair or maintenance.

The technical parameters of components, the type of functional failures, the contexts of the operation, the usages and the state monitors, and the relationships among them are also foundations for fault diagnosis. Fault diagnosis ontology can be used to describe the characteristics of the diagnostic object and its operating context [17; 20; 23] and the parameters describing state monitors [17; 21], in order to provide more details and more experience about the existing cases of fault diagnosis and to find out the deeper root fault causes for new cases.

# 3. USAGE OF FAULT DIAGNOSIS ONTOLOGY

In ontology-based fault diagnosis, how to use the fault diagnosis ontology is one of the decisive factors for the efficiency and effect of this method. At present, the usage of fault diagnosis ontology can be mainly divided into three categories: sharing domain vocabulary, reasoning for fault causes and retrieving information/calculating similarities.

## 3.1 Sharing Vocabulary

It is necessary to share fault diagnosis vocabularies before sharing domain knowledge and exchanging data when fault diagnosis is performed in the distributed environment. The fault diagnosis ontology facilitates domain vocabulary sharing in the distributed environments.

In a fault diagnosis system composed of multiple agents, each agent needs to understand and share the domain vocabulary of fault diagnosis in order to exchange information about the fault. Ontology is used as a tool and medium for managing knowledge from inter-domains or intra-domains, in order to ensure the commonality and consistency of information models. By sharing the vocabularies in the fault diagnosis ontology, multi-agents can coordinate actions when using Bayesian Networks for fault diagnosis [2], or can cooperate and negotiate with users and other agents in completing fault diagnosis tasks [1].

In the historical data for fault diagnosis collected from distributed environments, there are often cases in which the same parts are expressed by different and inconsistent vocabularies. The fault diagnosis ontology can then be used to clean the noisy data [19] and collect fine data [20]. It can also be used to improve the quality of knowledge extracted from repair verbatim collected from distributed or different sources [21].

### 3.2 Finding Fault Causes By Reasoning

As a domain knowledge base, the fault diagnosis ontology can be used directly or indirectly for reasoning to discover the fault causes and to provide repair or maintenance proposals.

The fault diagnosis ontology can be combined with rules to be reasoned by inference engines, targeting at finding out the root fault causes and inferring some repair or maintenance proposals. For example, using ontology and rules to represent the knowledge about fault diagnosis of rotating machinery, ontology reasoning can derive the fault cause of the rotating machine [4]. After modeling knowledge extracted from FMECA using ontology, ontology reasoning can help the maintenance personnel find the fault causes of wind turbines quickly and choose an appropriate solution to mend the wind turbines [31]. In the fault diagnosis method named HOS-MCFD, a fault diagnosis ontology is used for high-level semantic reasoning: first, the phenomena are mapped to the individuals represented in the ontology, after features are extracted from the sensor data and fault phenomena is detected by a machine learning method from the features; second, the ontology reasoning about the individuals finds the fault causes and the proposals for repair or maintenance [32]. In performing fault diagnosis for loaders, ontology is used in conjunction with rules to inference the fault cause, when shortage of similar fault cases occurs and case-based reasoning is insufficient for fault diagnosis. [28]. The fault diagnosis ontology is mostly represented by Ontology Web Language and combined with rules represented by Semantic Web Rule Language, when used for direct reasoning [17; 22; 25; 28; 31]. This helps to derive the fault cause by employing commonly used ontology inference engines such as JESS, Racer, Jena and Pellet.

The current research not only directly uses ontology reasoning, but also combines fault diagnosis ontology with other reasoning methods to build a more efficient fault diagnosis system. A multimedia service and resource management architecture for fault diagnosis is designed to include 3 types of automatic reasoning: heterogeneous, ontology-based, and Bayesian inference [2]. The combination of Bayesian inference and ontology-based reasoning performs better when incomplete data and uncertainties are encountered, and overcome the deficiency of data loss caused by failures of the devices for acquiring data. Fuzzy ontology technology is used to develop an improved ontology model for transformer fault diagnosis [22]. By introducing fuzzy inference, the problem of inaccurate fault diagnosis caused by the uncertainty or inaccuracy is solved.

### 3.3 Calculating Similarity/Retrieving Cases

The fault diagnosis ontology describes the information about the diagnostic object and creates a profile for the diagnostic object. Therefore, the fault cause and maintenance measures can be found by similarity calculation or case-based reasoning (CBR) when performing fault diagnosis, as long as there is a similar historical case.

The fault diagnosis ontology can be used to describe the case of fault diagnosis, calculate the similarity and store the case, thus providing a way to retrieve the case for fault diagnosis [5; 28; 30]. Since fault diagnosis ontology can represent multi-source heterogeneous information, it is used to provide more related information for retrieving similar cases of fault diagnosis [17]. In a clustering algorithm for extracting tuples from the keywords and find the the frequently co-occurring triples <symptoms, parts, the best maintenance practices>, fault diagnosis ontology is used to represent the keywords in the technician and repair verbatim. The ontology is also used in calculating of similarity metrics of fault diagnosis cases, yielding better clustering results [21].

## 4. SUMMARY AND PROSPECT

Recent studies have shown that the combination of fault diagnosis ontology with other technologies is the trend. By combining with other methods to obtain each other's complementary advantages, ontology is able to improve the efficiency and the effect of fault diagnosis. Through learning and leveraging existing knowledge about fault diagnosis, ontology-based intelligent fault diagnosis is able to discover unknown knowledge to handle new complex situations. There are two main factors that affect the performance of ontology-based intelligent fault diagnosis: the amount of domain knowledge and the ability to apply this knowledge to solve practical problems. Therefore, it is necessary to obtain more knowledge and use the knowledge appropriately.

In the era of big data, discoverying knowledge from data is a trend. Acquiring knowledge by data mining/machine learning for modeling fault diagnosis ontology is also necessary. At present, attempts have been made to combine machine learning and fault diagnosis ontology, such as fault symptom classification [32] and fault detection threshold determination [7]. The application of machine learning techniques in ontology engineering can extend the knowledge base and improve the quality of knowledge, such as the learning of concepts [12; 13] and learning relationship between concepts [9; 16]. Fault diagnosis ontology, a knowledge base, can also be further extended by machine learning to improve its ability in solving problems.

The most important advantage of fault diagnosis ontology is that it supports logical reasoning and semantic sharing of high-level concepts. The application of ontology in fault diagnosis should give full play to this advantage. Since fault diagnosis includes fault detection, fault isolation and fault identification, it completes tasks from processing raw sensing data all the way to finding fault causes and proposing repair/maintenance suggestions. The entire process of fault diagnosis not only requires ontology reasoning, but also needs data processing, feature extraction, semantic mapping, and so on. Therefore, the ontology-based fault diagnosis needs to be combined with other technologies and integrated into the whole process of fault diagnosis.

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