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Research on a knowledge modelling methodology for fault diagnosis of machine tools based on formal semantics

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ABSTRACT

Fault diagnosis is a critical activity in PHM (Prognostics and Health Management) of machine tools due to its great significance in such efforts as prolonging lifespan, improving production efficiency, and reducing production costs. An efficient knowledge model is necessary to build an intelligent fault diagnosis system. There have been several achievements in knowledge representation and modelling. However, due to their various purposes and depths, the established knowledge models are less compatible, reusable or transplantable, which restricts knowledge sharing and integration. A knowledge modelling methodology for fault diagnosis of machine tools based on formal semantics (KMM-MTFD) is proposed in this paper to build an open, shared, and scalable ontology-based knowledge model of fault diagnosis of various machine tools (OKM-MTFD). First, the proposed predicate-logic-based analysis method of fault elements is adopted to study the fault diagnosis domain and extract the common domain knowledge, which enables the establishment of the core ontology of OKM-MTFD to assure formal semantics. Next, using the proposed two-stage classification method of fault elements and external ontology reference methods, the core ontology can be extended into OKM-MTFD for a type or a specific machine tool. The knowledge reasoning and querying methods based on OWL axioms, SWRL rules, special fault attributes and SPARQL are provided to utilize the knowledge base efficiently. Finally, an ontology-based knowledge model and knowledge base of a hobbing machine tool is presented to exemplify the validity of the proposed KMM-MTFD.

1. Introduction

Machining systems that primarily consist of machine tools are used in a wide range of industries. For example, machining in China involves over 7 million machine tools [1]. However, due to poor working conditions and long service time, the machine tools are prone to breaking down and the same or similar faults tend to occur repeatedly, leading to huge costs and time loss. The high requirements and employment cost for fault maintenance personnel considered, a knowledge system able to meet the general requirements for fault diagnosis is most interesting for manufacturing enterprises. As machine tools and fault types vary significantly in different application contexts, even for the same type of machine tool, machine tool manufacturers require a knowledge system of fault diagnosis with great versatility to improve fault diagnostic services and reduce operation costs. Moreover, the knowledge system of fault diagnosis requires formal semantics to support customized nomenclature for different users and different occasions, which contributes to promotion in practical applications and acquisition of massive fault diagnosis knowledge for big data analysis.

"Smart Machine Tools" is an emerging topic of interest and the focus of recent industry initiatives, and fault diagnosis is an important part of machine health monitoring and an indispensable function of intelligent machine tools. With practical requirements and the development trend of intelligent machine tools, a modelling method based on knowledge for intelligent fault diagnosis has become increasingly important. In recent years, research on knowledge modelling has been developing rapidly [2]. The commonly used methods of knowledge representation are first-order predicate logic [3], production rule [4] and semantic network and framework [5]. Ontology can effectively combine the domain knowledge with information representation and has many advantages over other conceptual modelling technologies in classification, sharing, and formalization [6–8].

Knowledge modelling of fault diagnosis based on ontology has been paid much attention. Paper [9] conducted a comprehensive review on fault diagnosis orientation and noted that ontology

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Nomenclature

KMM-MTFD	knowledge modelling methodology for fault diagnosis of machine tools
OKM-MTFD	ontology-based knowledge model of fault diagnosis of machine tools
FP	fault phenomenon
FPA	fault phenomenon attribute
FM	fault maintenance
FMA	fault maintenance attribute
FC	fault cause
FCA	fault cause attribute
FL	fault location
FAA	fault auxiliary attribute

engineering and hybrid methodologies have great potential. They constructed an ontology-based knowledge-reasoning platform to address and recognize fault propagation scenarios. Paper [10] presented a semantic knowledge model of fleets in the marine domain based on ontologies for diagnostic purposes using a fleet-wide approach, providing managers and engineers with more knowledge and relevant and synthetized information regarding the system behaviour. Paper [11] explicitly introduced FMEA (Failure Mode and Effect Analysis) and used "can–cause" relations to correlate failure mode components, through which it presented a frame-based method to construct an ontology model for fault diagnosis. Paper [12] established a knowledge model of fault diagnosis for wind turbines by extracting concepts in FMECA (Failure Mode, Effects and Criticality Analysis). Though the paper studied the structures of most mechanic equipment including machine tools, commonality is still poor and the model is difficult to be modify, restricting the portability for other equipment. Paper [13] studied the concepts and relations of fault phenomenon, fault position, fault cause and fault solution, established a knowledge model based on ontology and constructed a knowledge base, which can be reasoned to a certain degree. However, the maintainability and scalability should be improved. Though ontology was adopted as the modelling tool, the ability of semantic representation is limited because the ontology model is targeted to a specific machine tool or purpose.

The existing ontology models of fault diagnosis can represent the main concepts, classification, relations and some restrictions according to specific machine tools' characteristics and actual needs. They can be rapidly modelled and easily carried out for specified machine tools or machinery with simple structure and few fault types. However, the problems listed below may restrict their promotion for various machine tools.

- Shortage of semantic expression. As the concept of an ontology class is too abstract and there are few limitations for syntax and semantics, the semantics of knowledge cannot be identified or checked by a reasoner for computers even if anything wrong occurs. The expression may diverge or be informal, inaccurate or even wrong due to different abilities, qualities and language habits of different knowledge engineers.
- Specific machine oriented. The established fault diagnosis models are relatively fixed, which makes it difficult to add to, update or/and delete any classes or relations. Once a model is changed, its existing knowledge may no longer be valid. Thus maintenance of knowledge is difficult, requiring quality staff and high cost.
- Weak inference ability. The existing models are able to realize reasoning to some degree, but only for existing knowledge. They are unable to test the results or analyse new faults.
- Limited transplantation ability. The knowledge model should be re-constructed for different machine tools to improve reusability and commonality for transplantation and promotion.

To address the aforementioned problems, this paper proposes a knowledge modelling methodology for fault diagnosis of machine tools based on formal semantics (KMM-MTFD) which provides unified domain ontology and methods for constructing an ontology-based knowledge model of fault diagnosis with versatility, flexibility and reusability for various machine tools. Section 2 analyses the development of fault diagnosis and knowledge modelling based on ontology and discusses the requirements for a practical knowledge system for fault diagnosis. Section 3 illustrates the concepts and presents the principle of knowledge representation in this study, and thus a novel knowledge modelling methodology for fault diagnosis KMM-MTFD including three layers, i.e., the core ontology layer, knowledge layer, and reasoning and querying layer, is proposed. Section 4 introduces the key methods and approaches in detail: (1) predicate-logic-based analysis method of fault elements; (2) core ontology of OKM-MTFD; (3) two-stage classification method of fault elements; (4) external ontology reference method; (5) construction approach of OKM-MTFD for a type of or a specific machine tool; and (6) knowledge reasoning and querying methods. Section 5 carries out an example for a hobbing machine tool using KMM-MTFD. Comparisons and discussions are presented in Section 6. Finally, the study's conclusions are presented in Section 7.

2. Background and related works

2.1. Development of fault diagnosis

Fault diagnosis is a process of locating the exact causes of a failure or fault and finding its most likely solutions. Generally, fault diagnosis technologies can be divided into three approaches, i.e., the artificial diagnosis method based on human experience, detection diagnosis method based on signal analysis and intelligent diagnosis method based on knowledge processing. The artificial diagnosis method based on human experience, which is heavily dependent on the abilities and qualities of maintenance experts, is achieved by evaluating the actual fault phenomenon and the field environment with maintenance experts' own experience and knowledge. The detection diagnosis method based on signal analysis detects probable fault locations using sensing and testing technology, and then analyses possible fault causes by signal processing, characteristics extraction and selection, pattern recognition and other data analysis technologies. Commonly used signal processing methods include time and frequency domain analysis [14], wavelet transform [15], EMD [16], etc.; commonly used pattern recognition algorithms include artificial neural network [17], support vector machine [18–20], Bayesian classification [21], fuzzy theory [22,23], etc. Intelligent diagnosis method based on knowledge processing, which is backed up with artificial intelligence and knowledge engineering, finds existing or hidden knowledge for fault diagnosis using inference engines. Representative methods include methods based on ontology models [11,24,25], expert systems [26,27], fault tree analysis [28,29], case based reasoning [30–32], etc.