Application of Ontology to Knowledge Management of Sucker-rod Pumping System Fault Diagnosis

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***Abstract*—Sucker-rod pumping system operating status fault diagnosis technology is closely related to the energy consumption, production per well and the cost of crude oil exploration. But the knowledge depiction of the expert diagnostic system is mainly based on the production rules, neural networks or object-oriented. As ontology has advantages in hierarchy and semantic relationships expressing, it is can be used in the knowledge management in the expert diagnostic system of the fault diagnosis technology. Then an ontology model for sucker-rod pumping system running state fault diagnosis system is also proposed in this paper. Basing on ontology, the knowledge management system framework is built up, which includes data layer, logic layer and application layer. The comprehensive diagnosis ontology database, including the knowledge domains of fault, collection and structure, is established. And the relationships among the ontology are described.**

***Index Terms*—Ontology, pumping system, fault, knowledge management**

I. Introduction

Sucker-rod pumping system (short of "pumping system") running state fault diagnosis technology has been one of the important issues in oil production engineering. This technology can affect the exploitation cost, energy consumption and the production per well. After 80 years of studies and practices, it has been greatly developed, especially, with the emerge of computer diagnostic technology, has entered into a new phase, i.e. it has developed from the qualitative analysis to the quantitative analysis [1], at the same time, it has stepped into the intelligent diagnostic phase [2]. There are four develop stages in pumping system fault diagnosis technology: ground indicator diagram analysis [3]-[5], downhole indicator diagram diagnosis method [6], computer diagnostics [7-12] and artificial intelligence diagnostic method [13-23]. The practical applications of this technology appeared after the emerge of expert systems [13], [14], [22], [23], neural networks [15] and pattern recognition technology [16]-[21].

The expert diagnosis system developed by H. J. Derk [13] has three main auxiliary programs: API, DHOLE and VIEW. By aid of the auxiliary programs, some tasks can be done: carry out the designs for conventional pumping device to get the rated operating parameters which are used as the reference data, calculate the hydrodynamic forces and inlet pressure of the pump basing on the transformation from the ground indicator diagram into downhole one, and so on. It also can help users to find out one certain fault group similar to the downhole indicator diagrams from all typical indicator diagrams in various kinds of fault group to check all indicator diagrams belong to this fault group. Then users can determine the fault category and get expert's explain and corresponding countermeasure.

The expert system developed by W. L. Foley *et al.* [14] is an auxiliary function module of the surface and downhole analysis program (SADA) which is a computer diagnostic technology. It includes a statistics-type model diagrams and a group of production rules featuring the form of "If-then". They are built up according to the expert experience and knowledge. The database has over 100 types of model diagrams corresponding to different typical failures of the pumping system, as well as more than 60 items of If-then rules of thumb, such as "If the downhole indicator diagram shows that the liquid level impact and pump inlet pressure is higher than the casing pressure, then it is indicated that the density of the liquid has changed or pump diameter is inappropriate ".

The pumping system fault recognition software developed by R. R. Dickinson *et al.* [16] established a standard indicator diagram library having about 30 kinds of corresponding typical pumping system faults. It is based on the indicator diagrams features: boundary chain code, boundary curve Fourier descriptors and boundary gray matrix. Incorporating pattern recognition techniques and the criterion of minimum Euclidean distance, the user

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can judge the operation status and diagnose, then give a proper countermeasure.

Basing on the study of R. R. Dickinson et al., G. A. Yu *et al.* [17] established a standard indicator diagram library with 17 categories of typical pumping system faults. The classification and identification to the pumping system operation status by aid of the criterion of minimum Euclidean distance and absolute difference distance, the correct recognition rate is greatly improved. After further improvements, through extraction of the statistical nature of the indicator diagram boundary grayscale matrix [18] and incorporating the sample average self-learning function and Fisher linear classifier [19], the recognition speed and accuracy was further improved. In present, this technology is widely used in oilfields of China.

Above mentioned diagnosis technologies and software are efficacious for single pumping system fault and it has verified an exciting economical benefit in increase crude oil production, reduce energy consumption and save workover cost. However, as to these techniques including expert system, neural network or pattern recognition, it is hard to carry out the knowledge and information acquisition, sensitivity and uncertainty reasoning, self-learning, and so on[24]. In other words, these techniques and software are immune to multi-factor fault. So it is necessary to develop an advanced diagnosis technology and software, which can be competent for multi-factor fault appeared in some production wells.

II. Ontology and Its Application

Ontology is one of the newly introduced fault diagnosis techniques in recent years. The conception of ontology originates from the philosophical conception which used to explain the nature of existence and relationship of objective things in ancient Greek philosophy [25] and [26]. On 17th century, Germany scholar first used ontology and interpreted it as a synonym of metaphysics. In accordance with the view of these scholars, ontology discourses various abstract and completely universal philosophical categories. Then from the abstract metaphysics, the duality, entity and causal phenomenon are derived. On a view of philosophy, it is used in the following two ways: "Yes" or "Existence". So, ontology is a innate principles system rely on the deducing from conception to conception [27]. It intends to uniformly conceptualize a certain definitional knowledge, then to look for the nature of all things from the natural internal and the relations among objects, and to build up the ontology of the objective world while braking away from the influence coming from human. In latest decade, the ontology is given a new definition and have gone far beyond the scope of philosophy. It is widely used in the fields of knowledge management, knowledge engineering and artificial intelligence. In modern information technology, ontology is defined as “conceptualization standardized explanation” [28]. These experts and professors, coming from the Knowledge Systems Laboratory of the Department of Computer Science in Stanford University, started a research plan named as “How Things Work” from the beginning of 1990s. The main purpose is to study the shared and reusable knowledge database which is for science and engineering and ontology-based. It has greatly promoted the researches of the ontology in knowledge engineering.

Ontology-based knowledge representation includes five modeling primitives: conception, attribute, relation, axiom and instance. It combines the advantages of the traditional method of knowledge representation and has rich knowledge representation languages. This can well realize the sharing and reuse of knowledge to make up for the defects of the traditional knowledge representation. According to the characteristics of the domain knowledge, select a most appropriate method to descript knowledge, and in terms of the complexity of this field, combine several techniques to form a powerful system to efficiently solve the intelligent problems. Therefore, there are more scholars choose ontology-based knowledge representation to descript the knowledge in the domain of mechanical fault diagnosis [29]-[34].

Y. Kitamura *et al.* [29] built up the ontology for steam engine fault diagnosis. The steam engine fault diagnosis ontology modeling has been investigated, including fault classification, fault representation. The aim is to develop an interactive system which can diagnose according to the users’ failure symptom description.

A. Bernaras *et al.* [30] introduced the ontology to the grid fault diagnosis, combining the traditional method, they established a diagnostic system based on the ontology failure event model. The system is able to reveal the deep reason in power plant failures.

The D. D. Dou *et al.* [31] proposed a fault diagnosis method based on ontology, explained the ontology-based fault diagnosis process, presented ontology-based fault knowledge representation and fault diagnosis algorithm. In the instance, the failure ontology consisted of 1000 conceptions.

In an automobile fault diagnosis expert system, N. Y. Shi *et al.* [32] used the ontology to realize knowledge sharing. The investigations showed that the different knowledge representation would cause the heterogeneity in various systems then be separated from each other and can not share and reuse the knowledge. This increased the difficulty of system development. So they also tried to use ontology to solve the heterogeneity of the expert system to realize the knowledge sharing.

L. Du *et al.* [33] applied ontology to construct an automotive engine fault diagnosis expert system. According to the reasoning characteristics of automotive engine fault diagnosis system, they discussed the construction of the domain ontology knowledge library, structure definition and system reasoning description.

Q. Niu *et al.* [34] proposed a knowledge description method basing on description logic in motor fault diagnosis, and the logical error detection reasoning has been done to the motor fault knowledge library. It can efficiently represent the relationship of the motor fault diagnosis domain knowledge and check out the error of knowledge logic system. During the experiment, the a diagnosis system was developed using the ontology editing tools protégé and OWL language, at the same time, realized the logical error detection reasoning through TABLEAU algorithm.

There are so many applications of ontology in fault diagnosis such as chemical process [35], AC motor [36], gear-hobbing machine [37], the air compressor [38]-[39], other rotating machinery [40], and so on. And it has captured the attentions of researchers in the field of pumping system [41].

In our study, an ontology model for sucker-rod pumping system running state fault diagnosis system was proposed. The knowledge management system framework is built up, which includes data layer, logic layer and application layer. The comprehensive diagnosis ontology database, including the knowledge domains of fault, collection and structure, was established. And the relationships among the ontology were described.

III. FAILURE KNOWLEDGE MANAGEMENT SYSTEM FRAMEWORK

In view of present oilfield production and organization structure characteristic, basing on ontology, this paper puts forward a pumping system running state fault diagnosis knowledge management system framework is show in Fig. 1.

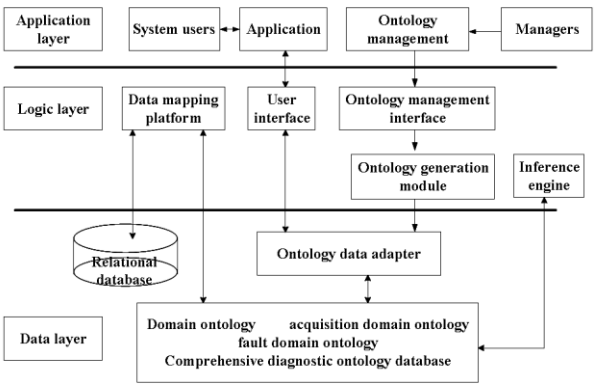

Figure 1. Knowledge management system framework

From Fig. 1 we can see that this model consists of a data layer, logic layer and an application layer. The relational database and integrated diagnostic ontology one in data layer are used to store related information of pumping system fault diagnosis.

The ontology database includes fault domain ontology, collection information domain ontology and structure domain ontology and they are three heterogeneous domain ontology. The ontology data adapter is for data exchange between ontology databases and data sets, while providing operation method for the interaction of the data in the ontology database. The logical layer data mapping platform is used to build the mapping relation between the traditional relational database and ontology library. The interface of ontology management and user can provide methods of access and modify ontology database for users. According to the data from the management interface, the ontology generation module generates a specified ontology structure. The inference engine is then capable of the heterogeneous ontology reasoning for ontology library and consistency detecting. The application layer is based on the logical layer, and the application program is intent to provide services of fault diagnosis information query, statistics and decision support system for ordinary users. The manager can edit the structure and content of the ontology through a specific interface.

IV. PUMPING SYSTEM FAULT KNOWLEDGE REPRESENTATION [38]

According to the characteristics of the pumping system fault diagnosis elements, it can be divided into three knowledge domains: fault domain (to express the knowledge of pumping system operating status fault classification, fault causes, and so on), collecting information domain (to express the acquisition information and operational knowledge of the pumping system) and structure domain (to express the knowledge about the hardware configuration of the pumping system). According to the characteristics of the structure and content of the information, the different information sources can be realized knowledge representation in its own ontology respectively. The heterogeneous knowledge of the three domain ontology is interrelated but all are basing on the fault integrated diagnosis ontology knowledge. The components of the domain ontology are shown in Fig. 2.

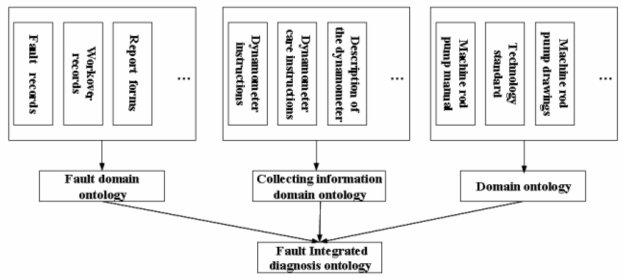

Figure 2. Domain ontology information constitutes

A. Fault Integrated Diagnosis Ontology

The fault integrated diagnosis ontology (FIDOnto) is a knowledge management model in which using ontology model to represent all kinds of information and their relationship with relevant to the fault diagnosis. It is expressed as:

FIDOnto::=(Id,C, A, R, S, Ax)

where Id identifies the name of the domain ontology, C is the concept set, A is the attribute set, R is the relation set, S is the body node status set and Ax is the axioms set of the field.

FIDOnto describes the common characteristics of all objects in a field. It is the parent ontology of the local ontology within this field, being equivalent to a knowledge base class. The fault domain ontology, collecting information domain ontology and structure domain ontology inherit the properties of the parent ontology, and been added to new members to describe the faults discipline from different views.

B. *Fault Domain Ontology*

The fault domain ontology (FaultOnto) is a knowledge management to describe the recorded information about the operational status failure mode of pumping systems, causes or workover. It is expressed as:

FaultOnto::=(Id, C, A, R, S, Ax,Bel)

where Id identifies the name of the domain ontology, C is the concept set, A is the attribute set, R is the relation set, S is the body node status set, Ax is the axioms set of the field, Bel is the credibility of values for the state. Specifically, C represents the pumping system running state failure modes or phenomena set, A is the set of failure characteristics, S is the set of fault state, the values ranging in "normal", "insufficient liquid supply", "traveling valve leakage ".

C. *Collecting Information Domain Ontology*

The collected information domain ontology (InfoOnto) is the knowledge management model to describe the condition monitoring information and the relationship including dynamometer, and dynamometer analysis. It is expressed as:

InfoOnto::=(Id, C, A, R, S, Indi, Ax)

where Id identifies the name of the domain ontology, C is the concept set, A is the attribute set, R is the relation set, S is the body node status set, Indi is the set of characterized indicators adn Ax is the axioms set of field.

D. *Structure Domain Ontology*

Structure domain ontology (StrOnto) is a knowledge management model to information and their relationship about the hardware configuration of the pumping system. It is expressed as:

StrOnto::=(Id, C, A, R, S, Ax, Spare)

where Id identifies the name of the domain ontology, C is the concept set, A is the attribute set, R is the relation set, S is the body node status set, Ax is the axioms set of he field, Spare is the standby conditions set of the objects.

E. *Ontology Connection Establishment*

The traditional similarity computing method can not effectively find the implicit relationship among the ontology and can not be directly used for the semantic association of the heterogeneous ontology mentioned above. Incorporating the Semantic Web Rule Language (SWRL) and Java Expert System Shell (JESS), it is efficacious to find the implicit semantic association among the ontology and realize the reusability and sharing of the heterogeneous ontology by establishment of rules and logical reasoning. The connection among the ontology can be expressed as:

M::=(C1, C2, Rel, K)

where $C1 \in O1$, $C2 \in O2$, C1 and C2 as a single concept in the ontology library, O1 and O2 is the ontology in different fields, Rel represents a connection relationship between two conceptions. The values range in makeUseOf, causedBy, independentOf, testAt. K indicates the connection credibility ($0 < K \leq 1$), K = 1 indicates the connection relationship is absolutely credible.

F. *System Implementation*

A traditional pumping system is show in Fig.3.

Its operation status directly affects the production, exploitation cost, energy consumption of the well. Therefore, state monitoring and fault diagnosis to the pumping system has been paid a great attention in oilfields, which is also one primary part of the digitization oilfield construction. Taking the pumping system as the research object, the feasibility of ontology-based fault diagnosis knowledge management system was verified.

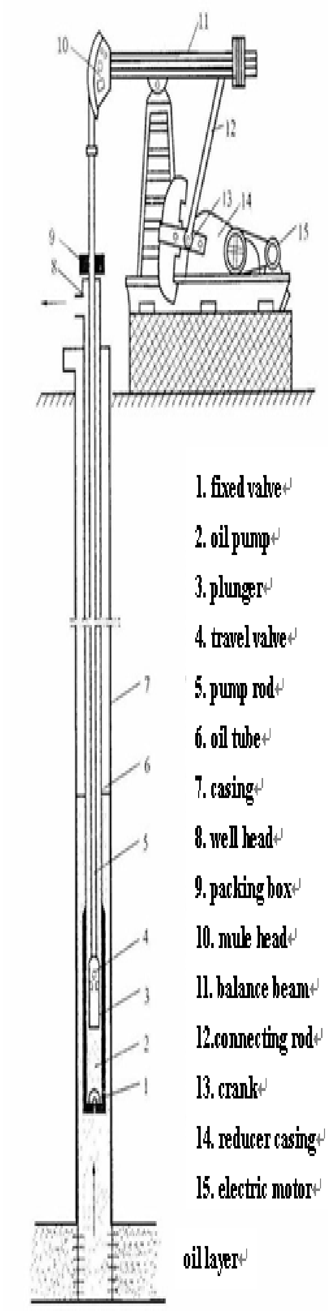

Figure 3. Pumping system constitutes

The Fault diagnosis ontology library of knowledge system is a foundation to realize the fault diagnosis knowledge management system. A large of data about the pumping system run history, structured, workover and diagnosis has been accumulated in oilfield production. Using protégé, we built a knowledge ontology database which has those data divided into above-mentioned failure domain, collecting information domain and structure domain. Fig.4 shows an instance of with ontology structure outputting from protégé the OWL Viz plug.

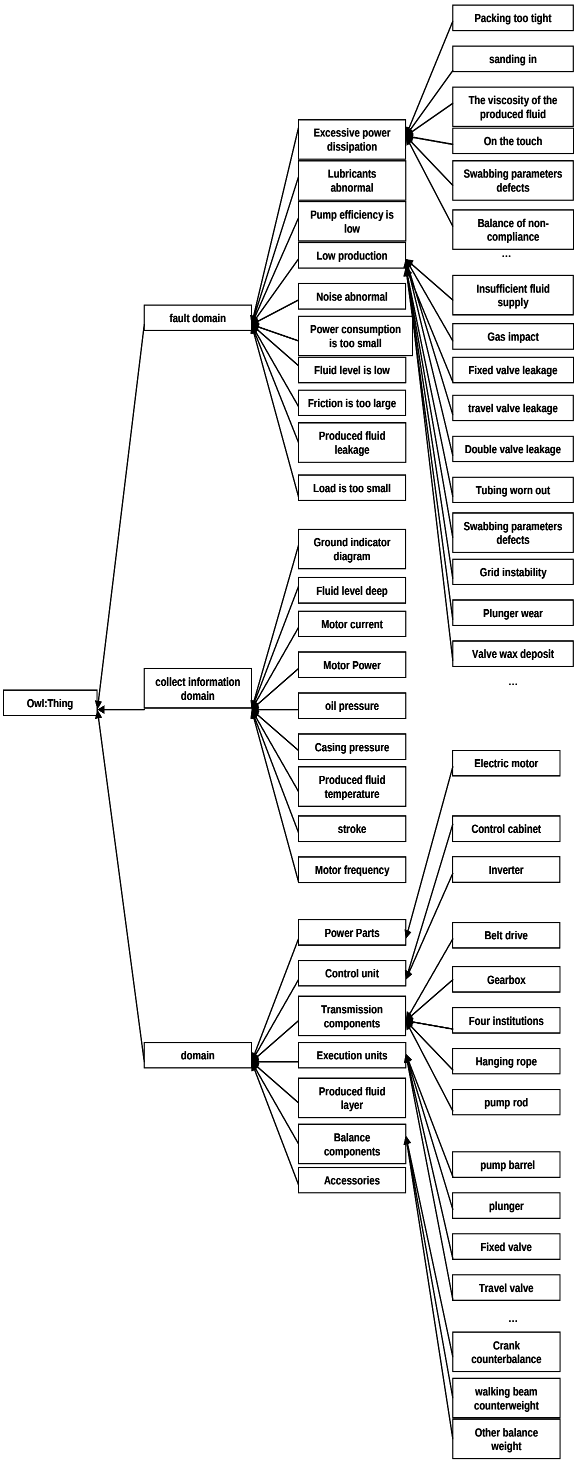

Figure 4. system part of the ontology model

The reasoning function of the logic layer of the knowledge system can be realized by then information interaction between Racer inference engine and the ontology library. And the interaction between the application layer and fault diagnosis ontology database is completed by data interface provided by the logical layer.

Data mapping platform provides language between a description ontology and relational database mapping relationship, and programming language Java API that can be used, thus to integrate the relational database of systems, which monitoring the operating status and fault of the existing oilfield pumping system, to a level of data layer of knowledge system. This data layer provides a common SPARQL for ontology database and relational database to query.

The nature of the data interaction between the application software and the ontology database is data retrieval in the ontology database. Comparing with the traditional keyword search system, ontology-based semantic retrieval system has a better performance: higher searching speed and accuracy. SPARQL, as the semantic query language recommended by W3C, has multi-data source query function and can perform the data retrieval of multi-source heterogeneous ontology.

The system users propose query requests according to their needs, and then the query processor in the application program executes the semantic expansion, reasoning query and SPARQL construction according to the requests. Semantic retrieval processing is a reasoning process, the constraints and axiom of fault knowledge ontology helps eliminate language ambiguity problem.

V. SUMMARIES

This paper proposed an ontology-based knowledge management system for sucker rod pumping system fault diagnosis. Basing on the ontology database, the operating status fault diagnosis information and knowledge can be reused and shared. The modeling of fault domain, collecting information domain and structure domain ontology is discussed in detail. A solution was proposed for the structural expression of the pumping system fault diagnosis knowledge. The designed knowledge management system has a clear conception of ontology and has merits of supporting interoperation among different systems.

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