Research Journal of Applied Sciences, Engineering and Technology 5(5): 1841-1847, 2013
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: August 11, 2012 Accepted: September 03, 2012 Published: February 11, 2013

Development of Knowledge Integration Model for E-Maintenance

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Abstract: In recent years, e-maintenance provides the opportunity for a new maintenance generation. Knowledge is one of core e-maintenance resources. To improve the efficiency of knowledge management and so as to improve the quality of e-maintenance work, a knowledge integration model for e-maintenance was proposed. The proposed model was made up of the relationships among role knowledge, task knowledge and equipment knowledge, to achieve the integration of maintenance business and knowledge resources. This study involved the following tasks: (1) developed the key components of the proposed model, including e-maintenance federation ontology, e-maintenance knowledge space and knowledge integration network; (2) designed the construction procedures for the proposed model; (3) presented an example to illustrate the application of the proposed model. Results of this study can improve the level of knowledge management for e-maintenance.

Keywords: E-maintenance, knowledge integration, knowledge management, ontology, plant maintenance

INTRODUCTION

The concept of e-maintenance in the industry refers to the integration of the information and communication technologies within the maintenance strategy and/or plan to service for plant maintenance (Holmberg *et al.*, 2010). E-maintenance is characteristic of knowledge intensive and collaborative (Levrat *et al.*, 2009). Each of Maintenance tasks requires employing of various knowledge and experience. Members of e-maintenance federation have the willing to share knowledge, so as to cooperate with other members and finish the maintenance work. Consequently, knowledge management is one of the important guarantees to the successful execution of e-maintenance.

At present, researches on knowledge management in e-maintenance mainly focus on the following three aspects: Relevant technologies to achieve knowledge sharing (Ivana *et al.*, 2005; Ren *et al.*, 2007); Resources sharing (include knowledge sharing) model or framework (Hung *et al.*, 2005; Jianwen and Dejie, 2012). However, in addition to the effective sharing, knowledge in e-maintenance also requires effective integration model to rapidly respond to the demand of maintenance work. This study proposes the knowledge integration model for e-maintenance, which is made up of the relationships among role knowledge, task knowledge and equipment knowledge, to achieve the integration of maintenance business and knowledge resources. The model can support the overall view of knowledge resources in e-maintenance and to achieve the effective organization and application of e-maintenance knowledge.

BUSINESS OPERATIONAL MODEL FOR E-MAINTENANCE

The business operational model for e-maintenance is shown as in Fig. 1. E-maintenance federation is a virtual organization in which different enterprise share the processes, activities and resources of maintenance to provide a value-add maintenance services. Maintenance Business (MB) is a value-add maintenance service. An e-maintenance federation can perform several MBs. A maintenance business can be divided into several Maintenance Tasks (MT). Maintenance Role (MR) is the divisions of duties in e-maintenance federation and each role reflects a position and rank in organization architecture. Maintenance Worker (MW) is a staff of federation enterprise which actual performed the MT. MR is assigned to MP to perform and MT is assigned to MR to perform. Mechanical Equipment (ME) is Mechanical device or Mechanical part in Mechanical device. Each ME is associated with one or more MTs and each MT is associated with one or more MEs. An integration model of knowledge must cover the following three elements f business:

- **Maintenance role:** Each maintenance role has different demand for maintenance knowledge. For example, as to a fault diagnosis expert, some knowledge about fault diagnosis theory will be recommended to knowledge user.

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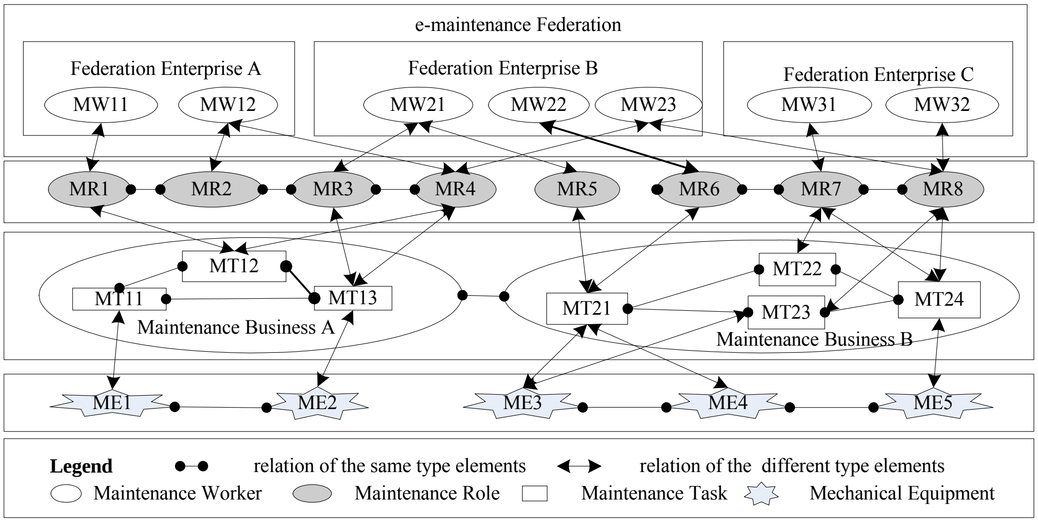

Fig. 1: Business operational model for e-maintenance

- **Maintenance task:** Each task needs distinct requirement of knowledge for fulfilling it. For example, when performing a task of fault diagnosis, some knowledge about fault diagnosis process will be recommended to knowledge user.
- **Mechanical equipment:** Maintenance task about different equipment requires different knowledge. For example, when the task is about compressor, some knowledge about structure of compressor will be recommended to knowledge user.

FRAMEWORK OF KNOWLEDGE INTEGRATION MODEL

The framework of knowledge integration model is shown as in Fig. 2. E-Maintenance Federation Ontology (EMFO) provides a common understanding for operational model of e-maintenance business. E-Maintenance Knowledge Space (EMKS) provides knowledge description model, which is the base of knowledge integration. Knowledge Integration Network (KIN) is made up of the relationships among role knowledge, task knowledge and equipment knowledge, to achieve the integration of maintenance business and knowledge resources.

Development of the model:

E-maintenance federation ontology: Ontology is an explicit, shared and formal description of important concepts and their relationships (Brewster *et al*., 2004). E-Maintenance Federation Ontology (EMFO) is to enable the federation members to share information on federation business for knowledge integration. EMFO can be expressed as:

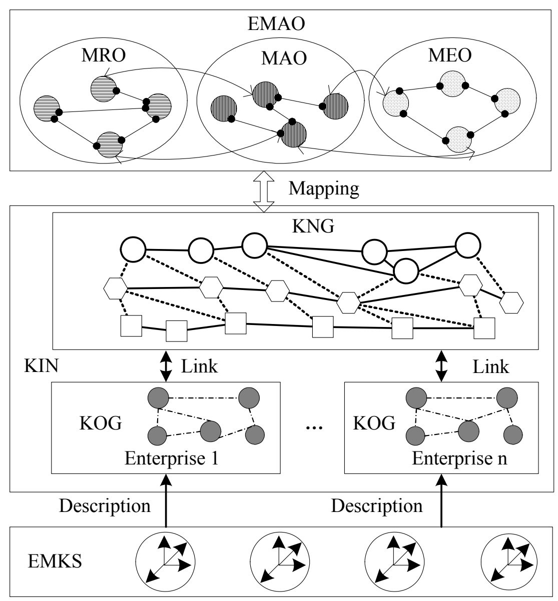

Fig. 2: Framework of knowledge integration model

EMFO = (C, R)

where,
C = Ontology concept set
R = Ontology relation set

Top level concepts and relations of EMFO are shown as in Fig. 3. Maintenance Activate Ontology (MAO) describes the activity concept and the relationship in the maintenance business. Maintenance Role Ontology (MRO) describes the role and relationship of the federation and maintenance members.

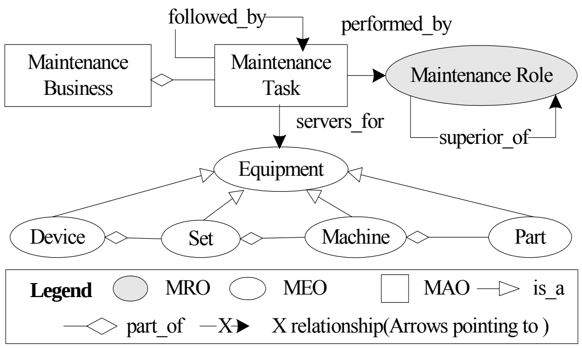

Fig. 3: Top level concepts and relations of EMFO

Table 1: Relationships of concepts in EMFO

Relation	Explanation
Part_of	CR (C_1, C_2) = part_of, concept C_1 is part of C_2
Is_a	CR (C_1, C_2) = is_a, concept C_1 is a category of C_2
Synonymy	CR (C_1, C_2) = synonymy, concept C_1 is synonymy of C_2
Followed_by	CR (C_1, C_2) = followed_by, concept C_1 is prior to C_2 in the process
Superior_of	CR (C_1, C_2) = superior_of, concept C_1 is superior to C_2 in the rank of role
Performed_by	CR (C_1, C_2) = performed_by, task C_1 is performed by role C_2
Servers_for	CR (C_1, C_2) = servers_for, task C_1 servers for equipment C_2

Mechanical Equipment Ontology (MEO) describes the concept and relationship of equipment and its parts and reflects the hierarchy and structures of equipment parts. Relationships of concepts in EMFO are shown as in Table 1 (CR is the relation function).

E-maintenance knowledge space: Knowledge space model is an n-dimension space, in which each point uniquely identifies a kind of knowledge resource (Zhuge, 2002). This study has extended the knowledge space model to construct E-Maintenance Knowledge Space (EMKS) to descript knowledge of e-maintenance. EMKS is represented as follows:

EMKS = (Background, Content, Application)

In EMKS, Background is sub space of knowledge background, which has the basic information of the knowledge, Content is sub space of knowledge content, which describes the content of knowledge; Application is sub space of knowledge application, which describes the applicable scope of the knowledge.

Background describes the background information of knowledge object. Background is represented as follows:

Background = (Owner, Author, Creation Date, Modify Date)

Table 2: Explanation of knowledge level

Level	Explanation	Format
Description	Knowledge about application information of knowledge objects	Text
Rule	Knowledge about rule	If-then
Procedure	Knowledge about process to achieve a goal or to solve a problem	Workflow
Case	Knowledge about case of problem solved	Problem-solve

Table 3: Explanation of knowledge sort

Logic	Explanation
Know-what	Knowledge about statement of something
Know-why	Knowledge about the reason of event, action and so on
Know-how	Knowledge about how to do something
Know-who	Knowledge about who can solve the problem

where,

Owne : Owner of knowledge object
Author : Author of knowledge object
Creation Date : The date when knowledge object is created
Modify Date : The date when knowledge object is modified

Content describes function of knowledge content. Content is represented as follows:

Content = (Category, Level, Logic, Version, Keywords, Abstract, Evaluation, Location)

Category defined by e-Maintenance Federation is classification of knowledge function. Level reflects different structures and storage forms of knowledge. Level classifies knowledge into five knowledge levels of “Description”, “Rule”, “Procedure” and “Case”. Explanation of each knowledge level is detailed as in Table 2. Logic classifies knowledge into five knowledge sort of “Know-What”, “Know-Why”, “Know-Who” and “Know-How”. Explanation of each knowledge sort is detailed as in Table 3. Version is the version of knowledge object. Abstract is abstract description of knowledge object. Keywords is a collection of words, which descript the function of knowledge object. Evaluation is evaluation value of knowledge quality. Location is the location of knowledge object.
Application is expressed as:

Application = (MRS, MTS, MES)

MRS is the role set, which describes the suitable roles of knowledge. MRS = {ROC_1, ROC_2,…, ROC_n}, ROC_i ($1 \le i \le n$) is the concept of the MRO. *MTS* is the task set, which describes the suitable takes of knowledge. MTS = {AOC_1, AOC_2,…, AOC_m}, AOC_j ($1 \le j \le m$) is the concept of MAO. MES is the equipment sets, which describes the suitable the suitable equipments of knowledge. MES = {EOC_1, EOC_2,…, EOC_P}, EOC_k ($1 \le k \le p$) is the concept of MEO.

Knowledge integration network: KIN is expressed as:

KIN = (KNG, KOG, NOLS)

where,
KNG : Knowledge node graph
KOG : Knowledge object graph
NOLS : The links of knowledge node and knowledge object

KNG is the mapping of the EMKO and is made up of knowledge nodes and their relations. KNG is expressed as:

KNG = (KNC, NNRC)

where,
KNC : Collection of Knowledge Node (KN)
NNRC : Collection of KN's relations and NNRC $\subseteq$ R

KN is expressed as:

KN = (ID, KC, P)

where,
ID : Identifier of KN
KC : Knowledge concept which adopts the concept of EMFO, namely KC∈C
P : The collection of KN, which defied by e-maintenance federation

NNRC is expressed as:

NNRC = (nnr_{ij}, $1 \le i \le n$, $1 \le j \le m$)

where,
nnr_{ij} : The relationship between two knowledge nodes

nnr_{ij} is expressed as:

nnr_{ij} = (kn_i, kn_j, nr)

where,
kn_i & kn_j: Knowledge nodes
nr : Relationship between kni and knj and nr∈R

KNG is used to show knowledge and the network structure by constructing the relationship among organization knowledge, business knowledge and equipment knowledge. In KNC, the concepts of maintenance role, task and equipment are all expressed as knowledge node. KNC also can be expressed as:

Table 4: Main types of relations in OORC

Type	Meaning	Explanation
Equ	Equal	Two KOs have the same content
Sim	Similar	Two KOs have the similar content
Imp	Implicature	The content of one KO contains another one
St	Subclass	The categorization of one KO is the sub-categorization of another one
Seq	Sequence	Sequence relationship between two KOs
Ref	Reference	One KO refers to another one
Inh	Inherit	The content new KO inherits the original one
Sup	Supplement	One KO is the supplement of another one

KNC = (RKD, AKD, EKD)

The RKD is knowledge domain of federation organization, RKD = {rkni, $1 \le i \le n$, rkni.kc∈MRO}, rkni is role knowledge node; AKD is the knowledge domain for maintenance business, AKD = {aknj, $1 \le j \le m$, aknj.kc∈MAO}, aknj is activate knowledge node; EKD is knowledge domain of equipment, EKD = {eknk, $1 \le k \le p$, eknk.kc∈MEO}, eknk is equipment knowledge node. KOG is made up of knowledge objects and their relations. KOG is expressed as:

KOG = (ID, ENT, KOC, OORC)

where,
ID : Identifier of KN
ENT : The enterprise which owns KOG
KOC : Collection of knowledge objects
OORC : Collection of KO's relations

In KOG, Knowledge Object (KO) is descripting by EMKS. OORC is expressed as:

OORC = {oor_{ij}, $1 \le i \le n$, $1 \le j \le m$}

where,
oor_{ij} : The relationship between two knowledge objects

oor_{ij} is expressed as:

oor_{ij} = (kr_i, kr_j, or)

where,
kr_i & kr_j : Knowledge objects
or : Relationship between kr_i and kr_j

OORC includes various associations which exist between knowledge objects. For example, the KO of a bearing fault and the abnormal knowledge of a bearing have the causal relationship. The main types of relations in *OORC* are shown in Table 4.

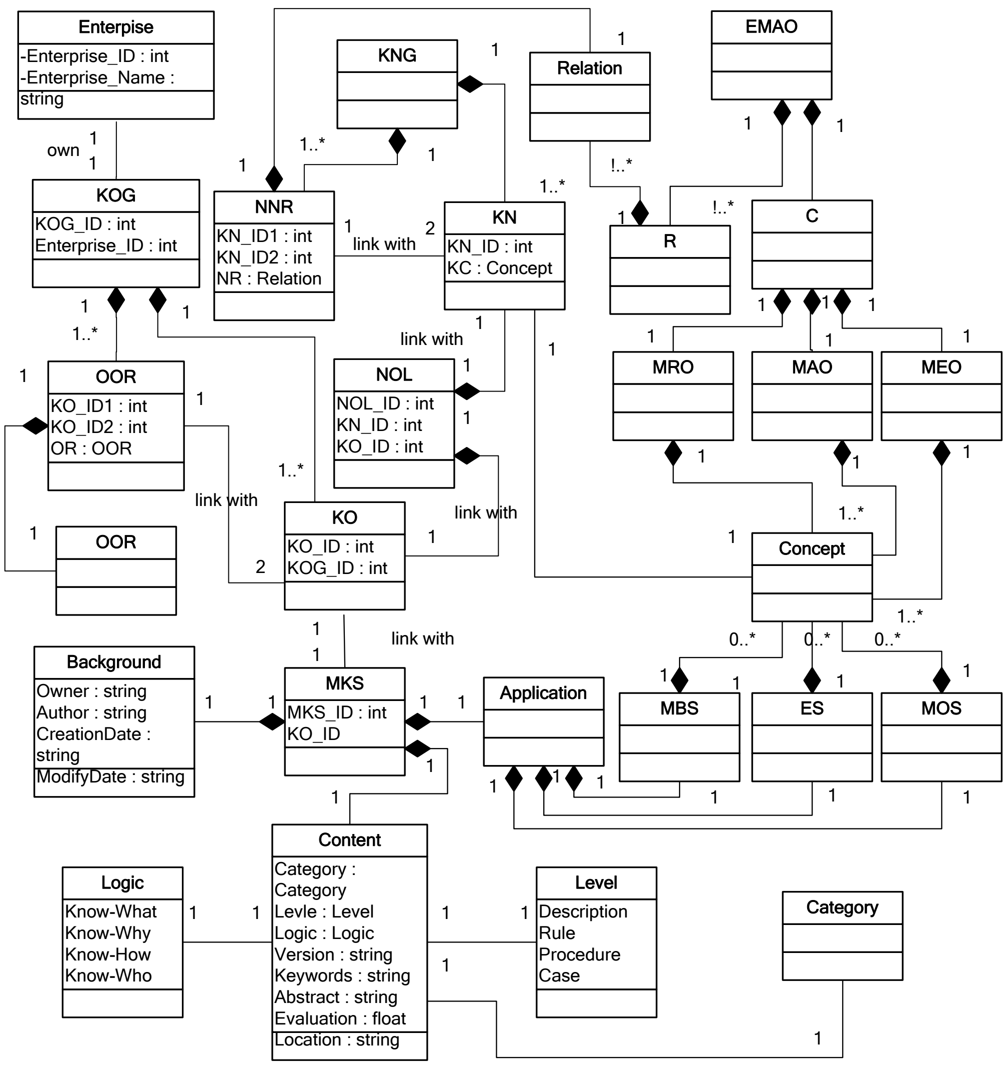

Fig. 4: Data structure of KIN

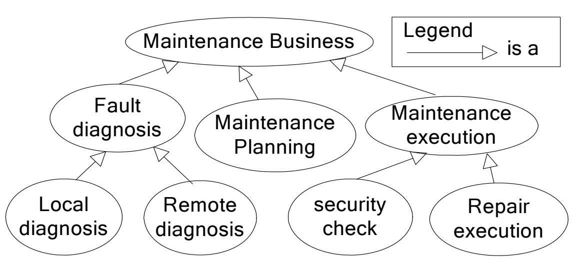

Fig. 5: Partial segment of MAO

The role of NOLS is to integrate KN and KO. NOLS is expressed as:

$$NOLC = \{nol_{ij}, 1 \le i \le n, 1 \le j \le m\}$$

where,
nol_{ij} : The link between a knowledge node and a knowledge object

nol_{ij} is expressed as:

$$nol_{ij} = (kn_i, ko_j)$$

where,
kn_i : Knowledge node
ko_j : Knowledge object

According to the above definition of KIN, this study designs the data structure of KIN, which is shown as in Fig. 4. In the KIN, concepts of MRO, MAO and

```
FOR EACH ontology concept Ci in EMAO
      CREATE kni
      SET kni.kc= Ci
      FOR EACH knowledge node knj in KNG
         IF CR(Ci, knj.kc) ∈R Then
               CREATE nnr=(kni, knj, CR(Ci, knj.kc))
                 ADD nnr in NNRC
     ELSE IF CR(knj.kc, Ci) ∈R Then
               CREATE nnr=( knj, kni, CR(knj.kc, Ci))
                 ADD nnr in NNRC
            END
   End FOR
End FOR
```

Fig. 6: Pseudo code of setting up KNG

```
FOR EACH koi in KOG
        FOR EACH ontology concept Cj in koi.Application
                FOR EACH knowledge node knk in KNG
        IF knk.kc= Cj Then
                        CREATE nol=(knk, koj)
                        ADD nol in NOLC
                End FOR
          End FOR
End FOR
```

Fig. 7: Pseudo code of integrating KOG into KNG

MEO are all expressed as knowledge nodes, one knowledge node can link with multiple knowledge objects; and one knowledge object can also link with multiple knowledge nodes. Each enterprise has its own KOG, so as to manage its knowledge resources. Each KOG of enterprise made up of KNG of e-maintenance federation. The relations of KN, the relations of KO and the links between KN and KO made up of KIN.

CONSTRUCTION PROCEDURES FOR THE MODEL

Procedures to set up the knowledge organization network are as follows:

- **Develop the EMKO:** Dominance enterprise in E-maintenance federation develops the ENKO and publishes it. Figure 5 is partial segment of MAO.
- **Set up KNG:** For each ontology concept in the EMAO, it set up a knowledge node and builds the relations between knowledge nodes. The pseudo code of setting up KNG is shown as in Fig. 6.
- **Set up KOG:** Enterprise descript and registers owned knowledge objects by EMKS; and then set up owned KOG.
- **Integrate KOG into KNG:** It can be achieved by creating links between KO and KN. The pseudo code of Integrating KOG into KNG is shown as in Fig. 7.

An example: Figure 8 is an example (a segment) of the model. It can be seen that maintenance worker can get the knowledge he needs when he is acting as a maintenance role and perform a maintenance task. Meanwhile, related equipment knowledge is available through the relation between maintenance task and mechanical equipment. For example (the bold part of Fig. 8) when maintenance worker acts as a "Diagnosis

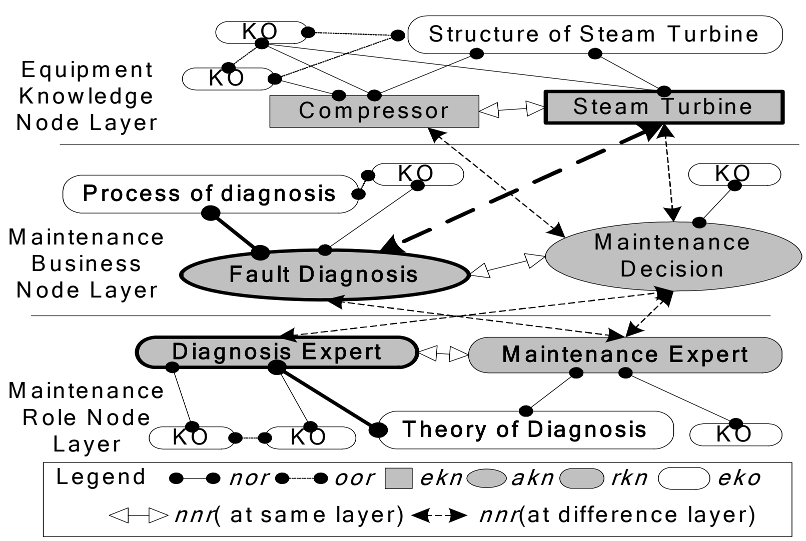

Fig. 8: An example (a segment) of the model

Expert", he can get the knowledge of "Diagnosis Expert" knowledge node (such as "Theory of Diagnosis"); when executing the diagnosis, the maintenance worker can obtain "Fault Diagnosis" knowledge node (such as "Process of Diagnosis"); if the task is to diagnose the fault of steam turbine, the "Steam Turbine" knowledge node can also be acquired (such as "Structure of Steam Turbine"). From the above examples, conclusions can be that the model can achieve knowledge navigation, knowledge supply and knowledge integration by maintenance business.

CONCLUSION

Knowledge is one of core e-maintenance resources and critical support element of maintenance process. The knowledge integration model is proposed to achieve the integration of maintenance business and knowledge resources. From the application examples, it is known that the model can support the navigation knowledge, supply activities and improve the efficiency of knowledge management.

ACKNOWLEDGMENT

The study is supported by the Research Starting Foundation from DongGuan University of Technology.

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