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Research on Visual Assessment Method for Maintenance in Virtual Environment Driven by Ontology

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Industry 5.0 has brought about explosive growth in data related to maintenance, especially in the field of virtual maintenance. The large-scale growth of data is difficult to avoid the problems of data fragmentation and heterogeneity, which brings new challenges to data-driven maintenance evaluation work. As a knowledge management tool, ontology can standardize the definition of concepts and the relationships between concepts. Applying ontology to standardize the expression of maintenance visibility related data in virtual environments, a virtual maintenance visual accessibility evaluation method based on ontology is proposed. This method uses a unified framework to standardize the semantic information related to maintenance visibility in virtual environments, solving the problems of knowledge expression errors and low communication efficiency caused by heterogeneity. It achieves innovation in virtual maintenance analysis and evaluation at the knowledge level, and is also an effective application and verification of existing domain ontologies.

Keywords: Virtual maintenance, maintenance visibility, ontology.

1. Introduction

Maintenance visibility evaluation is a critical component in the field of virtual maintenance, focusing on assessing the ease with which maintenance personnel can access and interact with components within a virtual environment. Traditional methods of evaluating maintenance visibility often involve manual analysis and simulations using computer-aided design (CAD) models. These approaches, while effective to a certain extent, have become increasingly insufficient in the face of the data explosion brought about by Industry 5.0. With the advent of Industry 5.0, which emphasizes the robust integration of humans and machines to increase value creation (Ordieres-Meré 2023), the volume of data related to maintenance processes has grown exponentially. (Mukherjee, A. et al. 2023) (Ivanov, D. 2023). This surge in data has led to significant challenges, particularly in terms of data fragmentation and knowledge heterogeneity. Data fragmentation occurs when maintenance data is dispersed across various systems, formats, and platforms, making it difficult to consolidate and analyze comprehensively (Ivanov, D. et al. 2019) (Ghobakhloo, M. et al. 2023). For instance, maintenance records, design specifications, and simulation data may be stored in disparate databases without a unified structure, impeding efficient access and utilization. Moreover, the lack of a unified framework hampers the ability to perform effective maintenance visibility evaluations. Without standardized representations and common semantics, automated tools and algorithms struggle to process and analyze data accurately. This inefficiency leads to increased time and resources spent on maintenance planning and reduces the overall effectiveness of virtual maintenance simulations.

Ontology offers a promising approach to overcoming the challenges associated with data fragmentation and knowledge heterogeneity in maintenance visibility evaluation (Ghobakhloo, M. et al. 2023) (Renda, A. et al. 2022). An ontology is a formal, explicit specification of a shared conceptualization, providing a common vocabulary and a coherent structure for representing knowledge within a particular domain (Studer, R. et al. 1998). By defining the concepts, relationships, and constraints relevant to maintenance visibility, ontology enables the standardization of data representation across different systems and platforms. This standardization ensures that all stakeholders and tools interpret the data consistently, reducing the likelihood of miscommunication and errors. Ontology facilitates the integration of heterogeneous data sources. Through semantic mapping and alignment, data from different formats and schemas can be translated into a unified ontology-based representation. This integration allows for comprehensive analysis and reasoning over the combined data set, which was previously fragmented. Furthermore, ontologies support advanced reasoning capabilities. The formalization of knowledge within an ontology enables the use of inference mechanisms to derive new insights and automate decision-making processes. This automated analysis enhances the efficiency and accuracy of maintenance visibility evaluations. Several studies have highlighted the benefits of using ontology in maintenance and manufacturing domains. For instance, Guo, Z. et al. proposed an ontology-based method for knowledge reuse in the maintainability design of complex products, demonstrating how ontology can facilitate maintainability considerations in the early design stages (Guo, Z. et al. 2024). Similarly, Zhou, Q. et al. developed approaches for knowledge reuse through ontology modeling and applied it to maintenance motion state sequences, improving the representation and application of maintenance knowledge (Zhou, Q. et al. 2024).

In the field of virtual maintenance, ontology plays an important role in creating more complex and intelligent maintenance planning and evaluation tools. Therefore, this article encapsulates expert knowledge and best practices in the ontology to provide more accurate maintenance visibility assessment results and further analyze maintenance difficulty. The proposed ontology addresses the issues of data fragmentation and knowledge heterogeneity by providing a unified and semantically rich framework for representing maintenance visibility information. Its ability to standardize concepts and integrate diverse data sources enhances communication efficiency and reduces knowledge expression errors. The application of ontology in virtual maintenance environments not only streamlines the evaluation process but also fosters innovation by enabling advanced analytics and intelligent decision support at the knowledge level.

2. Methodology

Following the top-down ontology development approach, existing ontologies were reused to achieve standardized expression of virtual maintenance visibility assessment. In this section, the framework and key classes of the proposed ontology will be introduced in detail.

2.1. *The framework of the Proposed Ontology*

When developing a new ontology, reusing existing ontologies has significant advantages and necessity, and is an important strategy. Reusing existing ontologies can significantly save time and resources, avoid building concepts, attributes, and relationships from scratch, thereby reducing repetitive labour and lowering development costs. In addition, reusing existing ontologies, especially those widely accepted standard ontologies, can promote interoperability between different systems, make data exchange and integration easier, and ensure consistent understanding of concepts and relationships among different systems.

The proposed ontology is aimed at solving the knowledge problem in the virtual maintenance visibility evaluation process and extending the evaluation of maintenance difficulty. Therefore, in the construction process, six ontologies related to maintenance work were selectively reused, namely:

- Basic Formal Ontology (BFO)

BFO is an upper-level ontology designed to provide a universal framework and structure for ontology development in different fields (J.N. Otte. et al. 2022). As an ISO standard (ISO/IEC 21838-2), BFO has been adopted by multiple international projects and organizations.

- Common Core Ontology (CCO)

CCO is a modular mid-level ontology designed to provide a universal and reusable set of core concepts and relationships for ontology development across different domains. CCO is built on the basis of BFO and extends the upper structure of BFO.

- Industrial Ontologies Foundry Core (IOF Core) ontology

IOF Core ontology is a mid-level ontology designed specifically for the industrial sector. IOF Core is built on the basis of Basic Formal Ontology (BFO) and Common Core Ontology (CCO), inheriting their formal rigor and modular design, while expanding and optimizing for specific needs in the industrial field (Hagedorn et al. 2019) (CUBRC 2020) (Drobnjakovic et al. 2022).

- Maintenance Reference Ontology (MRO)

MRO is a domain ontology specifically designed to support knowledge representation and system integration in the field of maintenance management. MRO aims to provide a standardized conceptual framework for equipment maintenance, repair, and operational management (Usman et al. 2013).

- Maintenance Motion State Sequence Ontology (MMSSO)

MMSSO is a novel ontology specifically designed to describe and maintain motion state sequences and their related processes in the field. MMSSO provides a new theoretical framework and technical tools for intelligent maintenance of complex industrial systems, with important academic value and industrial application potential (Qidi Zhou et al. 2024).

- Maintainability Design Ontology for Complex prOducts (MDOCO)

MDOCO is a domain ontology specifically designed for the maintainability design problems of complex products, aimed at providing a systematic knowledge representation and decision support framework for the product design phase (Ziyue Guo et al. 2024).

The proposed ontology is named Virtual Maintenance Visibility Assessment Ontology (VMVAO), which filters and extends the relevant content of maintenance visibility assessment based on existing ontologies, and comprehensively considers the special challenges that virtual environments bring to maintenance analysis work. Its framework is shown in Fig.1.

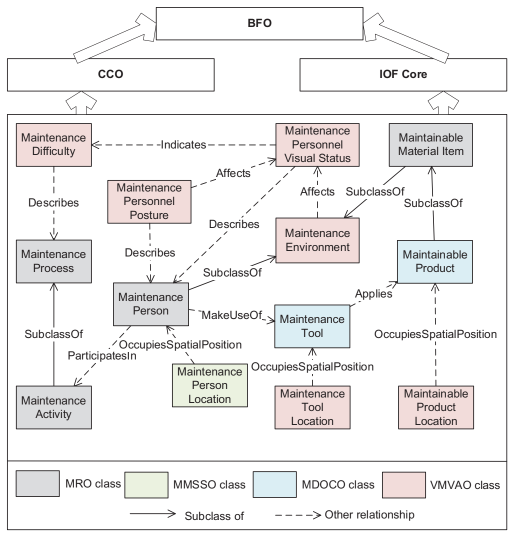

Fig. 1. The framework of the proposed ontology.

As shown in the figure, different coloured blocks indicate the ontology to which the class belongs. Due to the reuse of MRO and other ontologies during the establishment process of MMSSO and MDOCO, their original relationships were preserved. When evaluating the visual accessibility of virtual maintenance, it often involves three types of elements: human, machine and environment. Therefore, on the basis of the original ontology, relevant descriptions of the maintenance environment are added, and a new class is created. The VMVAO ontology is created for maintenance visual accessibility assessment and extended to maintenance difficulty assessment, therefore the creation of "Maintenance Difficulty" and "Maintenance Personnel Visual Status" is necessary. At the same time, considering that the environment in which the research object is located is a virtual environment, it is necessary to consider the differences between virtual environments and conventional environments, such as using three-dimensional coordinates to represent positions in virtual environments. Correspondingly, two classes, "Maintenance Tool Location" and "Sustainable Product Location," have been created. The 'Maintenance Person Location' is already defined in MMSSO. Further introduction to classes will appear in the next section.

2.2. *Key Classes of the Proposed Ontology*

The proposed ontology consists of 15 classes. In this section, the 6 newly proposed key classes are described and the axioms of the key classes are formally defined using description logic (DL) syntax (Baader et al. 2003).

- Maintenance Environment

This class describes the physical environment composed of people and equipment during maintenance activities, which can be divided into two subclasses: "Maintenance Person" and "Sustainable Material Item". Moreover, the "Maintenance Environment" can have an impact on a person's visual ability. The DL axiom defining this class is Eq. (1).

$$\begin{aligned} &MaintenanceEnvironment \equiv MaintenancePerson \sqcup \\ &MaintainableMaterialItem \sqcap \exists \\ &Affects.MaintenancePersonnelVisualStatus \end{aligned} \quad (1)$$

- Maintenance Personnel Visual Status

This class is the most critical class used to describe the level of virtual maintenance visibility because of its strong relationship with visibility. It considers many factors that may be related to visibility, including human capabilities and environmental parameters et al. Fig. 2 and Fig. 3 are examples of human abilities. For field of vision and visual range, the larger the field and range are, the stronger the human visual ability and the less stringent other external conditions are required.

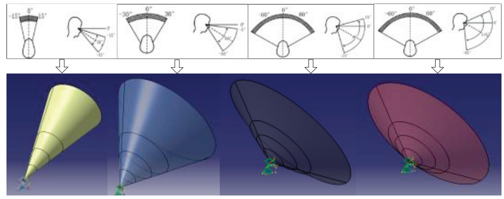

Fig. 2. Human field of vision.

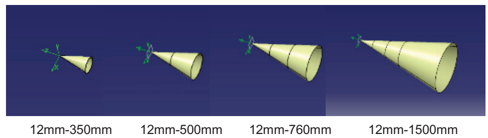

Fig. 3. Human visual range.

The DL axioms defining this class are as follows:

$$\begin{aligned} &MaintenancePersonnelVisualStatus \equiv \\ &\exists Indicates.MaintenanceDifficulty \\ &\sqcap \exists Describes.MaintenancePerson \\ &\sqcap \forall Affects.MaintenancePersonnelPosture \\ &\sqcap \forall Affects.MaintenanceEnvironment \end{aligned} \quad (2)$$

- Maintenance Difficulty

This class is based on visual assessment and is mainly influenced by visual status in this study. Here is the definition of this class.

$$\begin{aligned} &MaintenanceDifficulty \equiv \\ &\exists Describes.MaintenanceProcess \\ &\sqcap \forall Indicates.MaintenancePersonnelVisualStatus \end{aligned} \quad (3)$$

- Maintenance Personnel Posture

The posture of a person can affect their visual state. Correspondingly, human visual ability can also pose challenges to posture. Based on this definition, the following DL axiom is proposed.

$$\begin{aligned} &MaintenancePersonnelPosture \equiv \\ &\exists Affects.MaintenancePersonnelVisualStatus \\ &\sqcap \forall Describess.MaintenancePerson \end{aligned} \quad (4)$$

- Maintenance Tool Location

Due to the proposed ontology being considered in a virtual environment, additional knowledge representation related to localization is required. The DL axiom defining this class is Eq.(5).

$$MaintenanceToolLocation \equiv \exists OccupiesSpatialPosition.MaintenanceTool \tag{5}$$

- Maintenance Product Location

This class is similar to the previous person location and tool location. To define this class, the following DL axiom can be used:

$$MaintainableProductLocation \equiv \exists OccupiesSpatialPosition.MaintainableProduct \tag{6}$$

3. Case Study

In ontology engineering, Competency Question (CQ) is a core tool used to guide ontology design, validation, and evaluation. It defines a series of domain specific problems, clarifies the knowledge scope that the ontology needs to cover, the reasoning ability it should possess, and the practical application goals, thereby ensuring the logical completeness and practicality of the ontology. The CQs of the proposed ontology are described as follows:

CQ1: What is the evaluation result of maintenance visibility?

CQ2: What is the assessment result of maintenance difficulty?

Rule based reasoning (RBR) is a classic knowledge driven reasoning paradigm, whose core mechanism is to encode domain knowledge into "condition conclusion" logical pairs through formal rule sets, and use inference engines to achieve automated deduction from known facts to target conclusions. Semantic Web Rule Language (SWRL) rule is a formal language implementation of this paradigm in the semantic web domain. SWRL rules are based on semantic web standards, aimed at expanding the logical reasoning capabilities of Web Ontology Language (OWL) ontology. By combining OWL's descriptive logic and rule expression, SWRL allows users to define complex condition conclusion logic, supporting the derivation of implicit information from structured knowledge.

In order to verify, we instantiated the proposed ontology using the specific implementation process of virtual maintenance activities. During this process, the ontology formalized the knowledge related to visibility assessment in a standardized manner. At the same time, SWRL rules inferred the results of virtual maintenance visibility assessment and maintenance difficulty assessment.

```
<NamedIndividual IRI="#Visibility_evaluation">
<rdf:type rdf:resource="#MaintenancePersonnelVisualStatus"/>
<Status_value rdf:datatype="xsd:string">good</Status_value>
</NamedIndividual>
<NamedIndividual IRI="#M_posture">
<rdf:type rdf:resource="#MaintenancePersonnelPosture"/>
<Category_value rdf:datatype="xsd:string">stand</Category_value>
<Describes rdf:resource="#M_person"/>
</NamedIndividual>
<NamedIndividual IRI="#M_tool">
<rdf:type rdf:resource="#MaintenanceTool"/>
<Location_value rdf:datatype="xsd:string">wrench</Location_value>
</NamedIndividual>
```

Fig. 4. Example of Input Data.

For CQ1, visual assessment examples "?vs" (Visibility_evaluation) affects the difficulty evaluation instance "Difficulty_evaluation" through the "Indicators" attribute, and the implicit visibility result is "good". The SWRL rules and instantiation result are shown in Fig.5 and Fig.6.

```
vmvao:MaintenancePersonnelVisualStatus(?vs) ∧
vmvao:Status_value(?vs, "good") ∧
vmvao:MaintenancePersonnelPosture(?posture) ∧
vmvao:Category_value(?posture, "stand") ∧
vmvao:Describes(?posture, ?person) ∧
vmvao:MaintenancePerson(?person)
→ vmvao:Indicates(?vs, vmvao:Difficulty_evaluation)
```

Fig. 5. SWRL rules of CQ1.

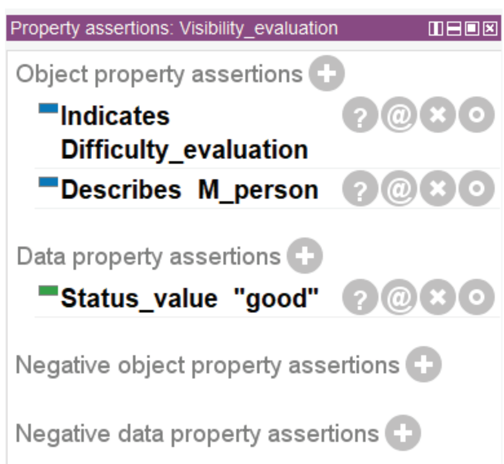

Fig. 6. Instantiation result of CQ1.

For CQ2, when the "Category_value" of the "Maintenance Environment" is "human repair APU" and the "Location_value" of the "Maintenance Tool" is "wrench", the difficulty assessment result is "easy". Fig.7 is the SWRL rules of CQ2, and Fig.8 is the instantiation result of CQ2.

```
vmvao:MaintenanceEnvironment(?env) ∧
vmvao:Category_value(?env, "human repair APU") ∧
vmvao:MaintenanceTool(?tool) ∧
vmvao:Location_value(?tool, "wrench") ∧
vmvao:MakeUseOf(?person, ?tool) ∧
vmvao:MaintenancePerson(?person) ∧
vmvao:Difficulty_value(vmvao:Difficulty_evaluation, ?diff)
→ vmvao:Describes(vmvao:Difficulty_evaluation, "easy")
```

Fig. 7. SWRL rules of CQ2.

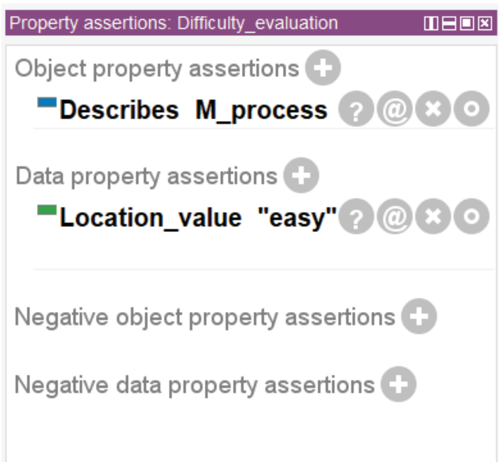

Fig. 8. Instantiation result of CQ2.

4. Conclusions and Future Remarks

A new ontology has been proposed to formalize knowledge related to virtual maintenance visibility assessment and extend it to derive maintenance difficulty assessment results. This ontology adopts a top-down design approach, based on Basic Formal Ontology (BFO) as the formal foundation, integrates the general conceptual model of Common Core Ontology (CCO), and integrates the industrial entity representation method of Industrial Ontology Foundry Core (IOF Core). After completing the ontology construction, the proposed ontology is instantiated and verified by simulating maintenance activities in a virtual environment.

The proposed ontology not only formalizes the relationships between concepts related to virtual maintenance visibility, but also overcomes the difficulties in expression and communication caused by knowledge fragmentation and heterogeneity. Moreover, the ontology also extends the inference evaluation of maintenance difficulty, which is an extended study of the impact of maintenance visibility level on maintenance difficulty.

Our research can be iteratively improved in the following areas in the future. Firstly, the breadth and accuracy of knowledge related to virtual maintenance visibility can be further optimized by increasing the number of consulting experts and setting selection rules for expert opinions during the collection and screening process. Secondly, some attributes in the ontology are set to string type, which slightly lacks the ability in quantization. Finally, the evaluation method for maintenance difficulty needs to incorporate more considerations and enrich the evaluation system in order to obtain more accurate results.

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