Proceedings of the 35th European Safety and Reliability & the 33rd Society for Risk Analysis Europe Conference
Edited by Eirik Bjorheim Abrahamsen, Terje Aven, Frederic Bouder, Roger Flage, Marja Ylönen
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doi: 10.3850/978-981-94-3281-3_ESREL-SRA-E2025-P6280-cd

A computer-aided evaluation method of maintenance operation space based on knowledge reuse

Qidi Zhou

School of Reliability and Systems Engineering, Beihang University, China. E-mail:qidizhou@buaa.edu.cn

Dong Zhou

School of Reliability and Systems Engineering, Beihang University, China. E-mail:zhoudong@buaa.edu.cn

Ziyue Guo*

School of Reliability and Systems Engineering, Beihang University, China. E-mail:guoziyue@buaa.edu.cn

Yunfeng Lu

School of Reliability and Systems Engineering, Beihang University, China. E-mail: lyf@buaa.edu.cn

YuShu Xie

Beijing Institute of Technology Press, China. xysrse@buaa.edu.cn

Abstracts: Industry 5.0 requires the manufacturing industry to realize the human-centric maintenance task for complex industrial tasks. It forces designers to reserve sufficient maintenance operation space during the early digital prototype design phase of the lifecycle, which is difficult to balance digital design for complex system with small space and compact layout. At present, designers conduct virtual simulation and analysis for maintenance operation space based on subjective experience. This digital method relies heavily on subjective expertise and manual iterations, leading to inefficiencies and inconsistent outcomes, which caused by the lack of visual model representation of subjective experiences and the absence of intelligent computer-aided technologies. Hence, a study on computer-aided evaluation of maintenance operation space based on knowledge reuse is proposed. First, an Applied Ontology for Maintenance Operation Space Evaluation (AOMOSE) for common structural components and activities are constructed. Second, an AOMOSE application which combines computer-aided and natural semantic processing technology is proposed to achieve four-step rapid analysis, including value matching, position obtaining, model import and positioning, and model interference detection. A case study on an aircraft APU starter-generator demonstrates this knowledge reuse method's effectiveness and feasibility. This method is a fusion of knowledge engineering, maintenance design, natural semantic processing, and computer-aided technologies. It explores the feasibility to achieve advanced maintenance in industry 5.0.
Keywords: Knowledge reuse, Maintenance operation space, Computer-aided technology, Maintenance design

1. Introduction

The advent of Industry 5.0 marks a paradigm shift in manufacturing systems towards human-centric operational frameworks (Maddikunta et al. 2022). This transition imposes augmented demands on maintenance tasks at the end stage of the lifecycle. These growing demands arises from the characteristics of manufacturing systems involving human-in-the-loop configurations and multilevel complexity maintenance operations (Siew et al. 2020). These characteristics further require to reserve enough maintenance-oriented space margin for digital prototype at the start of the lifecycle (Konstantinov et al. 2022). This early intervention can simplify life-cycle management by minimizing redundant design iterations and related resource expenditures to advance the transition toward green circular economies.

The predominant technical strategy adopted in the current Original Equipment Manufacturers (OEMs) is the virtual maintenance simulation-analysis method. It requires maintainability engineers to construct a virtual environment based on digital prototype and conduct ergonomic assessments for the maintenance operation on the current design based on subjective experience (Geng et al. 2018). Subsequent function designers adjust the spatial layout and form a closed-loop optimization process under the assessment results and specified functional specifications. This method has demonstrated operational efficacy in complex manufacturing systems including aircraft (Bernard et al. 2020), space satellites (Luo et al. 2021) and ships (Song and Li 2023).

However, the prevalent virtual maintenance simulation-analysis method exhibits two critical limitations: (1) over-reliance on expertise in ergonomic and design, leading to subjective differences design outcomes and (2) iterative lag in design cycles caused by manual feedback integration of digital prototype between different design participants. These dual limitations stem from the non-standardized implementation of maintenance related information across lifecycle phases, especially the lack of interoperable digital prototype application to ensure the traceability between different design stages.

To address the critical factor of maintenance operation space in in design-for-maintainability, this study proposes a computer-aided evaluation study of maintenance operation space based on knowledge reuse. First, to ensure the consistency and objectivity, an Applied Ontology for Maintenance Operation Space Evaluation (AOMOSE) is constructed for common structural components and maintenance activities. Second, to reduce the iteration lag, a rapid positioning and analysis application based on AOMOSE is proposed through the integration of computer-aided design (CAD) assistance and natural language processing (NLP) techniques. Finally, the effectiveness of this proposed method is demonstrated through a maintenance case study of a starter-generator system. It explores the feasibility of achieving advanced maintenance in Industry 5.0 through based on digital prototype.

This study is structured through four logically sequential sections. Section 2 introduces the main methodology, including AOMOSE and its application. Section 3 validates the proposed method through a case study. Finally, Section 4 summarizes the paper and details possible further work.

2. Methodology

The proposed methodology adopts a definition-application framework to systematically address maintenance operation space challenges. First, an AOMOSE ontology is constructed based on Basic Formal Ontology (BFO) (Otte, Beverley, and Ruttenberg 2022) good practice and knowledge reuse. The aim is to ensure the consistency and objectivity of information for subsequent applications. Second, an AOMOSE application is proposed by integrating NLP within CAD-assisted technologies. It can achieve rapid positioning and visualization evaluation for maintenance operation space based on the above ontology.

2.1. *AOMOSE: the applied ontology for maintenance operation space evaluation*

In this subsection, AOMOSE is constructed to formalize the expression in the application for maintenance operation space evaluation. This ontology describes the semantic definitions of various terms in this evaluation process. The objectives are twofold:

(i) integrate and express consistency definitions
(ii) assist evaluation to output objective results.

2.1.1. *The development of AOMOSE*

AOMOSE is developed from top to bottom in a four-tiered pyramid shape by reusing ontological and nonontological knowledge. The four layers consist of top-level ontology, intermediate ontology, domain ontology and application ontology. The top-level ontology is the BFO. The intermediate ontologies are the Common Core Ontology (CCO) and industrial ontologies foundry core (IOF Core) ontology. The domain ontology is Maintenance Reference Ontology (MRO) (Karray et al. 2019), Maintenance Motion State Sequence Ontology (MMSSO) (Zhou et al. 2024) and Maintainability Design Ontology for Complex prOducts (MDOCO) (Guo et al. 2024). The application ontology mainly reuses the above classes and relationship in the above ontologies. Considering the characteristics of application ontology, AOMOSE integrates 18 class structures through systematic reuse of domain-specific ontologies: 5 classes from MRO, 10 classes from MMSSO and 3 classes from AMCDO. The reusing process is the conceptual embodiment of the sustainable integration of ontological and nonontological knowledge. The selection of the 18 reused classes refer to the non-ontology knowledge embodied in the application process. The taxonomic definitions directly reuse the ontology knowledge in domain ontologies. The main 14 relationships also directly reuse the existing ontological knowledge. The four-tiered pyramid shape of AOMOSE is shown in Fig. 1. The classes and relationships in AOMOSE are visualized, as shown in Fig.2.

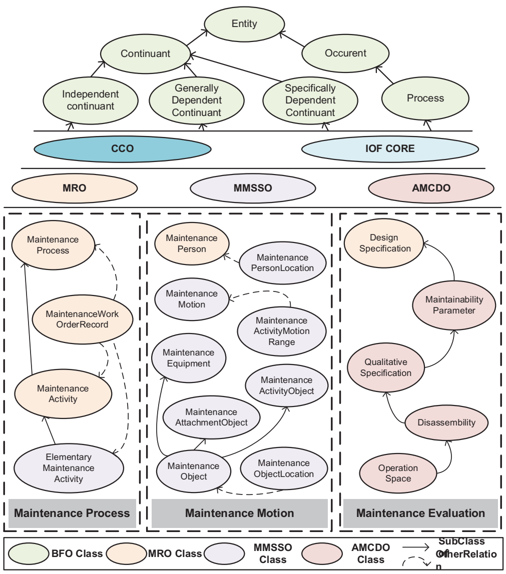

Fig. 1.The framework of AOMOSE

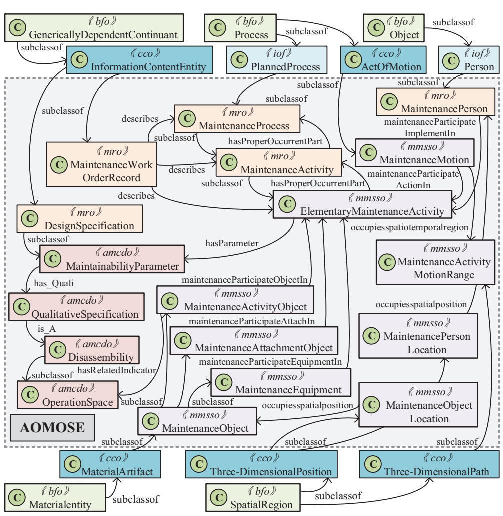

Fig. 2.The classes and relationships of AOMOSE

Furthermore, the Competitive Questions (CQs) are designed to guide the AOMOSE application. The following CQs are proposed respectively from two perspectives: pre-use input and output-organization.

(i) What are the input elements for maintenance operation space evaluation?
(ii) What is the evaluation result of the operation space corresponding to the maintenance object?

2.1.2. *The verification of AOMOSE*

AOMOSE is verified by combining SWRL reasoning and SPARQL queries to answer CQ1 and CQ2. This combination method can output the comprehensive results and the hidden inclusion relationships. The verification process is depicted in Fig. 3 below. The blue dotted line indicates the rules of SWRL reasoning. The brown double-dotted line denotes the rules of the SPARQL query. The left part reports the corresponding AOMOSE parts of CQ1 and CQ2.

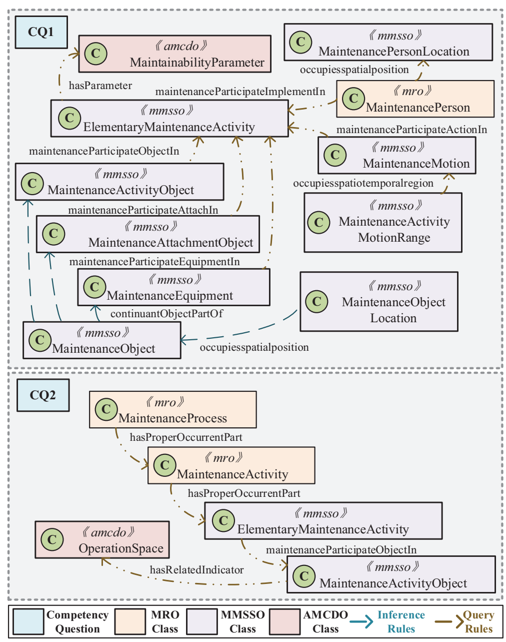

Fig. 3.The verification process of AOMOSE

The corresponding outputs to these CQS are the input elements and the corresponding evaluation result. The output of the upper part (CQ1) is the input elements for maintenance operation space evaluation. It is obtained by combining SPARQL query and SWRL reasoning to query the hidden chain relationship between maintenance objects and maintenance items from objects to activity, location and range. The output of the lower section (CQ2) is the evaluation result of the operation space corresponding to the maintenance object. It is obtained by SPARQL queries from object to activity and then to evaluation. Therefore, the CQs of AOMOSE have been verified to provide consistency and objectivity knowledge to the evaluation.

2.2. *A rapid positioning and visualization analysis AOMOSE application*

The AOMOSE application is proposed to reduce iteration lag caused by the current maintenance operation space evaluation method. It integrates NLP within CAD-assisted technologies to achieve rapid positioning and visualization analysis. This computer-aided technology can also ensure consistency and objectivity in the evaluation process.

The application input comes from AOMOSE and digital prototype respectively. The ontology input is transformed from the original maintenance manual into the generated instance, and then to the query and reasoning result based on CQ1. The digital prototype input is from the structure tree, parameters and three-dimension coordinate in the virtual environment.

The specific application steps are divided into four steps. The first step is the semantic matching of information through NLP-based hierarchical pattern recognition. It can systematically map operational entities (including person, motion and equipment) to their corresponding virtual models based on lexical-semantic attributes. The second step is to extract and process the corresponding coordinate data. It integrates API interfaces from virtual environments with knowledge engineering module acquire three-dimensional data of object, person, motion and equipment. The third step is to import and position the maintenance operation visualization model. It imports the maintenance operation space model according to the types of motions and activities firstly. Then it realizes the positioning according to the obtained coordinate data and pose matrix. The fourth step is to achieve quantitative evaluation for maintenance operation space. It combines the range-based interference detection in the API interfaces to realize the detection of different ranges. In conclusion, with the four steps in the CAD-assisted application, it can obtain the quantitative results of maintenance operation space evaluation. The framework of this application is shown in the Fig. 4 below.

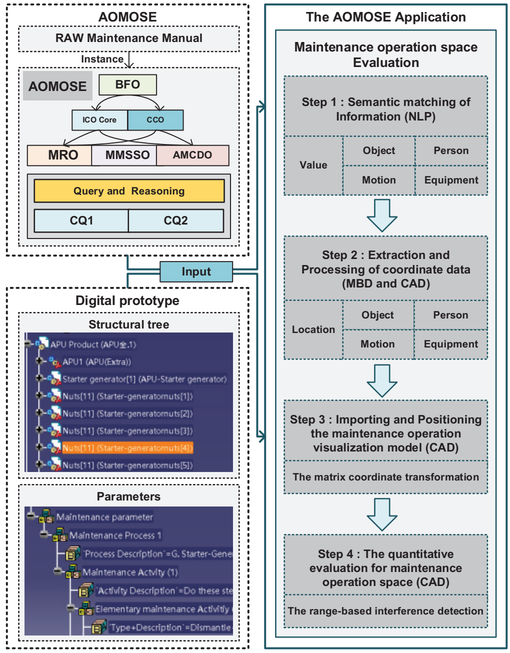

Fig. 4.The framework of AOMOSE application

3. Case study

This case study verifies the AOMOSE and its application. The objects of verification are the elementary maintenance activity of an APU starter generator for a large passenger aircraft. AOMOSE is verified by answering the CQs related to instances of the maintenance activities established above. The AOMOSE application is verified by rapid positioning and visualization analysis. These evaluation results are discussed by comparing with current methods. In addition, the limitations and effectiveness of the method are discussed.

3.1. *Semantic verification of AOMOSE*

AOMOSE is verified by answering the CQs through SWRL reasoning and SPARQL queries. The instances used for verification are created based the raw maintenance manual. The corresponding outputs are the pre-use input (CQ1) and output organization (CQ2). The CQ1 is verified before the maintenance operation space evaluation. It is answered by reasoning and querying the output data, including the value of person, motion and equipment and the types of maintenance object. For instance, it can output data required for evaluation, including motion "Disconnect", motion paradigm "E2MKG3", object "the electrical connector", object location "X, -198.234" and other data. The CQ2 is verified after evaluation. It can quickly output evaluation result for each elementary maintenance activity. For example, it can organize and output the quantitative evaluation results "60 Scope" and "90 Scope", which represents for its allowable operating range of 60 and 90 degrees.

3.2. *Feasibility verification of AOMOSE application*

The AOMOSE application is verified through rapid positioning and visualization analysis for an APU starter-generator removal activity. The detailed 4-step verification process is shown as Fig. 5 follows. For the nuts on the starter-generator, in step 1 and 2, the corresponding value and position data are matched and extracted first from ontology and digital prototype. It then obtains the position of the virtual human, the wrench motion in the range of 60-90 degrees, and the position and pose matrix data of the nuts. In step 3, three maintenance operation space visualization range models are imported and located to the relevant positions by the pose matrix coordinate transformation. In step 4, these models are performed the interference detection separately with the open API in the virtual environment. The middle model meets the 90-degree range, while the upper and lower models are limited by the narrow space and can only meet the 60-degree range.

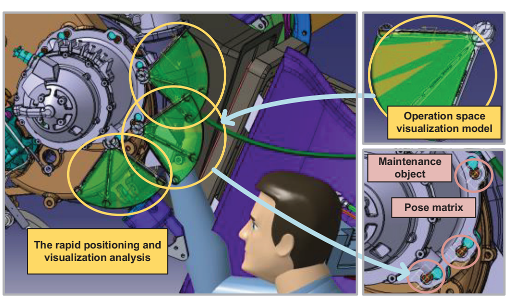

Fig. 5.The semantic verification for AOMOSE CQs

3.3. *Discussions*

Through this case study, the proposed ontology and its application method are validated. The results are mainly discussed in five respects:
First, AOMOSE can answer the pre-use input and output-organization CQs to guide the application. It is verified by answering the CQs through reasoning and querying. The output results for answering CQ1 are motion "Disconnect", motion paradigm "E2MKG3", object "the electrical connector", object location "X, -198.234" and other data. These query and reasoning can convert the original maintenance manual into the required input of the subsequent applications. The output results for answering CQ2 are the quantitative evaluation results "60 Scope", object "nut" and corresponding activity " (c) Remove the four nuts [4] from the four terminal studs". The CQ2 is queried after the operation space evaluation. It can organize the related information relationship, which is convenient for designers to view different activities, objects and evaluation results.
Second, the AOMOSE application is verified feasible by integrating NLP within computer-aided technologies. It can realize rapid positioning and visual analysis for maintenance operation space. It realizes nuts evaluation through four steps: value matching, position obtaining, model import and positioning, and model interference detection. As shown in Fig. 5, three nuts have operation space ranges of 60, 90 and 60 degrees respectively. With the current evaluation method, designers need to select the wrench model according to their own experience, import and adjust the position of the wrench model, spend a lot of time on the animation, and subjective judge operation allowable range. Compared with the current method, this computer -aided method can struggle out people's subjective experience and achieve rapid and effective verification.
In conclusion, this article proposes a computer-aided evaluation method of maintenance operation space based on knowledge reuse. Considering two unavoidable shortcomings of the current method: subjective differences and design iteration lag, this paper first proposes the application ontology AOMOSE through knowledge reuse to ensure the consistency of multi-source heterogeneous information. Then it proposes an AOMOSE application to realize

rapid positioning and analysis by integrating NLP CAD-assisted technologies. It can help function designers directly realize quantitative judgment to reduce the iteration delay caused by the sequence of different stages in the design cycle.

4. Conclusions

This study presents a novel methodology for computer-aided evaluation of maintenance operation space based on knowledge reuse, addressing the challenges of human-centric design in Industry 5.0. By constructing the application ontology AOMOSE, it firstly ensures consistency and objectivity in maintenance operation space evaluation through systematic knowledge reuse and semantic formalization. Subsequently, it integrates NLP within CAD-assisted technologies to enable automated spatial mapping, rapid positioning, and quantitative interference detection, significantly reducing reliance on subjective expertise and iterative delays inherent in current methods. The case study on an APU starter-generator system validates the feasibility of the approach, demonstrating its capability to transform maintenance manuals into actionable inputs, visualize operation ranges, and deliver quantifiable evaluation results. Compared to conventional simulation practices, this method enhances efficiency by streamlining data interoperability and automating spatial analysis, thereby advancing lifecycle management for complex systems.

Future work will focus on the combination of extended ontology and Model-based definition (MBD) to cover dynamic maintenance scenarios, and integrate real-time collaborative design feedback to further meet the flexible and people-centred intelligent manufacturing vision of industry 5.0.

Acknowledgement

This work is supported by China Postdoctoral Science Foundation under Grant Number 2023M730167.

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