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ARTICLE

KGAssembly: Knowledge graph-driven assembly process generation and evaluation for complex components

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ABSTRACT

The semantic information of process documents for the assembly of complex components plays an important role in the guidance of assembly operations and the feasibility evaluation of process plans. There are many types of semantic elements contained in assembly process documents. The semantic relationship between assembly elements is complex. Additionally, there is a lack of effective modeling method to deal with the implicit associative semantic knowledge that exists among existing assembly process cases. In this case, it is a great challenge to use the professional knowledge in assembly process documents to guide the intelligent decision-making of assembly process planning and the intelligent analysis of assembly process enforceability evaluation. In this paper, a knowledge graph-driven assembly process generation and evaluation method for complex components is proposed. An APKG (assembly process knowledge graph) model is built. A distributed graph embedding-based model SKGCN (sequence knowledge graph convolutional network) is designed to generate assembly process planning. Furthermore, model and knowledge dual-driven evaluation method for assembly sequences is presented. It provides assembly expert knowledge support for the evaluation method of interference detection of assembly sequence based on point cloud assembly feature recognition. Finally, the approach is evaluated by assembling an aero-engine compressor rotor.

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Knowledge graph; graph embedding; assembly sequence; assembly evaluation; complex components

1. Introduction

The assembly of complex components is an important stage for industrial product manufacturing. According to relevant data statistics, in modern manufacturing, assembly hours account for 40%~60% of total product R & D (research and development) and production hours (Liu 2018). The assembly of aero-engine belongs to a complex product. Its assembly is typically single-piece and low-volume production modes. In the case, the traditional automation and information technology are gradually showing the limitations in the stage of assembly process planning (Soshkin 2016). The assembly process planning stage takes up a high proportion of the total assembly time in the modes. In other words, it is not easy to generate assembly process planning rapidly for customized products. The causes are mainly reflected in the following.

(1)Lack of reuse the knowledge to intelligently guide assembly operations.

The generation or planning of assembly process can essentially be viewed as a cognitive intelligent operation that depends on expert knowledge and experience. Currently, the assembly information is mainly managed by PDM (product data management) system (Ruan et al. 2015). However, the large amount of information accumulated in the assembly stage is transformed into the expression of professional knowledge at a very low level. In particular, the assembly knowledge mainly comes from process documents and CAD models. Specifically, the process documents contain a lot of heterogeneous information. There are many types of semantic elements contained in assembly process documents. The semantic relationship between assembly elements is complex. In addition, there is a disconnect management between the CAD models and documentation of the assembly process. These lead to difficulties in generating and reusing expert knowledge or experience in the assembly process, but relies more on manual instead of automatic.

(2) Low evaluation efficiency of assembly process scheme.

The automation of assembly process evaluation is low in aerospace industry. Currently, the assembly

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process planning is mainly managed by CAPP (computer-aided process planning) system (Leo Kumar, Jerald, and Kumanan 2015). Once a vast number of assembly process schemes are given. The digital management system does not have the cognitive ability like a domain expert to quickly filter some unreasonable assembly sequences. Besides, the professional engineers need to be involved in the evaluation. This reflects the fact that the evaluation system lacks the empirical knowledge like an expert to evaluate the reasonableness of multiple process schemes. Empowering an assembly evaluation system with expert knowledge is a viable idea to address the efficiency of evaluation of assembly plans.

In brief, in order to generate expert knowledge to guide assembly operations, it is necessary to build an assembly information model that can integrate information from the CAD model and the assembly process. Currently, there are several approaches to model assembly process information, including object-oriented model (Wang et al. 2010), XML-based model (Bao et al. 2013), Petri network-based model (Yang, Han, and Pan 2014), and ontology-based model (Sayed and Lohse 2014). Specifically, the object-oriented model is difficult to handle the information interaction between heterogeneous systems. The XML-based model can satisfy interoperability requirements between heterogeneous systems, but only describe the structure of the assembly process, which makes it hard to express the implicit semantic information in the assembly process. The reusability of the Petri network-based model is clearer than that of the object-oriented model. However, it is still not conducive to interoperability between heterogeneous systems. Ontology-based model is widely used in the industry. It is a standardized description language that is good at describing the interaction between assembly semantics and heterogeneous systems. However, its semantic description is complex. There are many rules in the semantic model. In addition, ontology represents knowledge on the schema layer without a description of deep semantic relations. Industrial ontology is a collection of resource concepts, which mostly describes resource concepts and their attribute information. Thus, it is not suitable for processing large-scale knowledge. Knowledge graph (Chen, Jia, and Xiang 2020) is a structured semantic knowledge base, composed of the triples with entity-relationship-entity and entity-attribute-value, which can better describe the heterogeneous information both in the data and schema layer. Knowledge Graphs can interface with neural network algorithms to reason about expected entity and relationship link information in complex knowledge networks. And this causal information is interpretable when presented as local subgraphs in a knowledge graph network.

In this paper, a knowledge graph-driven assembly process generation and evaluation method for complex components is proposed. First, for integrating the information between process documents and 3D model, the assembly information model is established to generate the APKGD (assembly process knowledge graph database). Then, the graph embedding model SKGCN is designed to generate the assembly process sequences. Based on the input assembly feature information, knowledge network links for potentially plausible assembly processes are output. Besides, model and knowledge dual-driven evaluation method for assembly sequences is presented. The method is divided into two steps, including interference filtering of assembly sequences method and feasibility evaluation of non-interference sequences method. The former method mainly solves the projection areas of the point clouds of base assembly feature and non-assembly feature in the xOy, yOz, and xOz planes, so as to realize the assembly sequence evaluation for assembly interference detection in steps. The latter method is mainly used to calculate the available solutions in the remaining assembly sequence after filtering the interference sequence. Furthermore, Taking the assembly of rotor parts of an aeroengine compressor as an example, the proposed method can realize the rapid filtration of unreasonable assembly process.

The main contributions of this paper are as follows:

(1)A knowledge graph-based information model of the assembly process is developed to reveal the formation mechanism of assembly process knowledge. The heterogeneous information related to assembly resources is tackled to generate a unified assembly structured knowledge network. The knowledge network can support the assembly process generation method to reason the expected entity and relationship links information.

(2)A distributed graph embedding-based model SKGCN is designed to uncover the generation mechanism of assembly process sequences. The method is developed to learn the implicit associative semantic knowledge in existing assembly process cases. The plausible assembly process sequences are generated based on the graph embedding information. The embedding information contains the complex assembly relationship links from the structured graph network of the APKGD.

(3)A model and knowledge dual-driven two-stage approach is proposed for assembly sequence interference calculation and non-interference sequence enforceability evaluation. The purpose is to calculate the available assembly sequence among multiple plausible assembly sequences.

(4)The proposed method is evaluated by assembling an aero-engine compressor rotor. The results indicate that the proposed method can employ the assembly process knowledge to generate the assembly sequences and find the available assembly sequences efficiently. It is a reference value for increasing the intelligence level of assembly process planning.

The remainder of the paper is structured as follows. Section 2 briefly summarizes the related work. Section 3 gives the method of constructing the APKGD. In section 4, the evaluation of assembly sequence is driven by assembly process knowledge. Section 5 takes the assembly of rotor parts of an aeroengine compressor as an example to demonstrate and verify the proposed framework. Finally, the conclusions and limitations of this study are summarized in section 6.

2. Related work

As discussed in the preceding, the basic idea of improving the low efficiency of assembly process planning is to build assembly process knowledge model and evaluate the assembly sequence. Therefore, many scholars have carried out a lot of successful research on assembly process information modeling and evaluation.

2.1 Modeling and generating methods of assembly process knowledge

The assembly process information of the product includes the geometric information of the parts and the non-geometric information of the assembly process. The essence of the assembly process information model is the organization form of the information (Tian et al. 2012). Currently, there are several approaches for modeling assembly process information. (Xu et al. 2014) presented an object-oriented assembly process information model to abstract and encapsulate the complex assembly relationships in the assembly process. It can simplify the assembly process description of complex products. And it is beneficial to solve the combinatorial explosion problem. For the information interaction problem of each module in the virtual assembly system (Zhang et al. 2014) introduced an XML-based assembly process information model focusing on describing the assembly structure information. (Wang et al. 2015) established a Petri network-based assembly process model for the problem of optimal scheduling of production lines for the aircraft assembly process. (Gruhier et al. 2015) proposed a formal ontology approach based on spatio-temporal subtopology for ensuring the consistent management of product design information and the associated semantic information of the assembly sequence. The ontology-based assembly process information model (Qiao, Zhu, and Anwer 2015) created the data structure of product geometry information in the assembly process based on ontology. And the OWL-DL ontology language is used to describe the product geometry information, assembly process information and the relationship between them. In recent years, information models based on knowledge graph have been gradually applied in industry. (Li et al. 2018) proposed a structured modeling method of heterogeneous CAM model and process knowledge reuse based on process knowledge graph, which realized the unity of semantic representation of process knowledge. The pros and cons of these methods are summarized in Table 1.

In addition, it has the ability of intellectual reasoning to update the information in the knowledge base. Knowledge reasoning is mostly knowledge complement and link prediction, including translation-based model (Bordes et al. 2013), convolution neural network-based model (Nguyen et al. 2019), recurrent neural network-based model (Wang et al. 2018), reinforcement learning-based model (Wang et al. 2019), graph convolution network-based model (Vashishth et al. 2020). These models are all embedded representations of nodes and edges in triples. The pros and cons of these methods are summarized in Table 2.

In summary, in order to improve the usefulness of the assembly process information model, this study adopts a knowledge graph-based assembly process information model to extract the assembly semantics from

Table 1. The pros and cons of various assembly process information models.

Method	Pros	Cons
Object-oriented	Abstraction, stability and reusability	Difficulties in handling information interactions between heterogeneous systems
The XML-based	Meeting interoperability requirements between heterogeneous systems	Only describe the assembly structure information and lack the implicit semantic information.
Petri network-based	Stability, reusability and clearer expression than the object-oriented model.	Lack of handling interoperability between heterogeneous systems.
Ontology-based	Facilitating description of assembly semantics and interaction between heterogeneous systems.	Language descriptions are complex and rules are needed to express semantics
Knowledge graph-based	Good at describing heterogeneous information and can interface with neural network algorithms to reason the implicit information in complex knowledge networks.	Knowledge processing involves a variety of technologies. It is difficult to master the characteristics of each type of technology for applying to specific business scenarios

Table 2. The pros and cons of knowledge reasoning models.

Method	Pros	Cons
Translation model-based reasoning	Describing knowledge as semantic vectors.	Lack of ability to handle multi-relational semantics.
Convolutional neural network-based reasoning	It is suitable for large-scale and zero-shot knowledge reasoning	Lack of interpretability for the semantics contained in triples.
Recurrent neural network-based reasoning	Allowing multi-hop reasoning across multiple relationship types.	Modeling complex structures may be unrepresentative and may not provide sufficient information.
Reinforcement learning-based reasoning	Search the relationship paths to obtain a multi-hop indirect relationship between entities.	Self-learning reasoning strategies and reward functions work poorly.
Graph convolutional network-based reasoning	Graph neural networks are naturally adapted to represent graph data. It can reason complex data efficiently	The kernel of the graph network needs to be further optimized to represent the graph structure well only in certain domains.

electronic process documents and CAD models. Knowledge reasoning based on a distributed graph embedding-based model. It is convenient for reuse of assembly process knowledge.

2.2 Planning and evaluation methods of assembly process

The assembly process planning includes assembly sequence planning and assembly path solving. Automatic generation of assembly process for complex components mainly involves the assembly sequence planning. Currently, there are several types of methods for assembly process planning. (Thomas, Stouraitis, and Roa 2015) proposed an assembly sequence exclusion algorithm based on assembly association AND/OR graphs. The infeasible assembly sequences are excluded by human-computer interaction considering the matching priority and assembly stability. (Lin, Sheng, and Chen 2017) extended the geometric constraints of the assembly to the three-dimensional space. The assembly process is planned according to the assembly angles. However, this method divides the three-dimensional space into thousands of directions, which is prone to the problem of computational explosion. (Zhou et al. 2019) reviewed the existing main disassembly based sequence planning methods in terms of disassembly methods, disassembly modeling and planning methods. (Zhong et al. 2018) abstracted the knowledge and empirical semantics required for assembly sequence planning into an ontology model. The ontology reasoning is implemented to judge the rationality of assembly sequences. The pros and cons of these methods are summarized in Table 3.

In conclusion, a better approach is knowledge-based assembly sequence planning. But it is generally achieved by pre-defining assembly rules. Therefore, the generalization is not high. The reason for this is the lack of a better description of the semantics of assembly. As a result, in this paper, the

Table 3. The pros and cons of various assembly sequence planning methods.

Method	Pros	Cons
Assembly constraint priority-based	Non-geometric constraints; simpler computation; better reliability	Requiring human-computer interaction; low efficiency; It is not suitable for complex assemblies.
Geometric constraint priority-based	Being free from human-computer interaction and reducing human error.	When there are more geometric constraints or the assembly is complex, it is prone to computational explosions.
Disassembly-based	Being used for assemblies of any geometry	When the assembly is complex, it is easy to combination explosions.
Knowledge-based	Process knowledge and experience can be reused, it has good applicability to similar objects.	Low efficiency in building ontology knowledge base; Low generalization of rule-based reasoning methods