Information Modelling Method of As-built Process Data

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Abstract. The digital twin concept plays a significant role in the Industry 4.0 era since it was proposed. One key enabling technology for digital twin creation is the information modelling of physical products. Therefore, the modelling approach to modelling as-built process data of physical products, which faithfully reflects the real machining status, emerges to be pivotal. This paper addresses the problem of modelling as-built process data in machining process, which is difficult to accomplish by relevant methods, and hinders data reuse and the long-term archiving. Furthermore, an ontology-based information modelling method of as-built process data is proposed as the recommendation to represent and record the data in the cyberspace. It provides a standardized process for companies to model as-built process data by specifying the contents to be modelled, and the modelling method. To validate the effectiveness, a case study is undertaken in an aviation manufacturing plant at last. The result shows that the proposed information modelling methodology is readily to the virtualization of as-built machining process data.

1. Introduction

Manufacturing companies today are facing many challenges, including mass customization, predictive manufacturing systems, and rapid response production [1]. To meet the needs of intelligent manufacturing and mirror the actual status of the physical objects, the digital twin (DT) concept was introduced by Grieves in 2011. Later in 2011, United States Air Force research laboratory adopted the DT concept as a new way to predict the aircraft structural life. In 2012, National Aeronautics and Space Administration (NASA) defined DT as “an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, and so forth, to mirror the life of its flying twin”. According to the latest study, the answer to the challenges mentioned above may reside in the creation and applications of DTs [2]. Since the concept was brought forward in 2011, it has been applied in various industrial fields such as smart building information modelling (BIM) [3], maintenance of nuclear plants [4], assembly of high precision products [5], and some other scenarios of modern manufacturing [6-13]. It is suggested that DT can reflect the dynamic mapping of physical product and its digital counterpart and it is the technical core of cyber-physical system (CPS).

However, how to apply the DT concept to the machining process has not attracted enough attention due to the insufficient research of the applications [14]. It is suggested that DT-based machining process knowledge reuse could help engineers optimize the process planning [15]. In order to discover
hidden machining process knowledge, the priority is to model all the real process data. At present, most of the latest research are focused on the complex scenarios and how to model the real process data under the guidance of the DT concept in a practical way still remains blank, which hinders the real process data reuse and long-term archiving. Besides, the real process data of a machining part stored in the e-documents or even paper documents are easily ignored because more attention is paid to the qualification rate when machining parts are delivered. To solve these problems, this paper uses the term “as-built data” in BIM to describe the real process data of the status as a machining part is finished. Furthermore, based on the above motivations, this paper proposes an information model method of as-built process data. The proposed approach using ontology web language (OWL) with industry standards is considered as the key contribution. A sample using a machining part produced in an aviation manufacturing company is presented as a case study. The remainder of this work is organized as follows: Section 2 reviews the related works and highlights the research gaps. The proposed information modelling method is presented in Section 3. A case study is presented in Section 4 to validate the method. Finally, discussion of the results, future direction of the research, and concluding remarks are provided in Sections 5 and 6, respectively.

2. Related works and research gaps

According to the published literature so far, the DT concept was introduced by Dr. Michael Grieves in 2011 [16]. Then in the next year, NASA defined DT as “an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, and so forth, to mirror the life of its flying twin” [17]. After several years, based on the initial assumption, kinds of definitions and explanation of DT had significantly broadened the concept. For example, DT was treated as the next generation of simulation [18]. Tao et al. believed that DT is a method to complete the convergence between physical and cyber spaces [7]. Especially, Michael Grieves redefined DT as “a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level and any information that could be obtained from inspecting a physical manufactured product can be obtained from its digital twin” [19]. Recently, DT refers to a virtual representation of manufacturing elements, a living model that continuously updates and changes as the physical counterpart changes to represent status, working conditions, product geometries and resource states in a synchronous manner [20].

It should be pointed out that the technical core of a DT is a data model that encapsulates physical data and information relationship with its external environment [21]. It is also suggested that knowledge representation tools such as ontology are potential choices for DT creation [22]. From this point of view, a common practice for DTs creation of as-built products is to build an information model using semantic web languages such as OWL [2]. Therefore, some studies had adopted ontology as a tool for the information modelling oriented to DT creation. Thus, the related works of semantic modelling in machining process oriented to DT creation are listed below.

2.1 Related works

2.1.1 The representation and exchange of product model. An approach to translate STEP schema into OWL is presented with a model called OntoSTEP [23]. The OntoSTEP model can be integrated with any OWL ontologies to create a semantically rich model by combining geometry information represented in STEP with non-geometry information. In a more recent study, Wan et al. focused on the creation methods of 3D machining process model by establishing machining ontology and modelling ontology [24]. These studies aimed to use the rich semantics of OWL to overcome the shortcomings of 3D product model.

2.1.2 The process planning and process knowledge management. Eum presented an ontology-based modelling method of the process planning knowledge for machining operation selection regarding multi-axis machining feature [25]. Solano et al. developed an ontology as a specialist offshoot of the
product and processes development resources capability ontology [26]. Qiao et al. presented an approach to modelling manufacturing process information based on some predefined ontologies [27]. The use of OWL provides a formal description for entities and their relationships. Therefore, the internal concepts in manufacturing process can be defined unequivocally by using OWL. These studies focus on the query and reasoning capabilities of OWL.

2.1.3 The manufacturing resource virtualization. Jang et al. demonstrated the virtualization of manufacturing resources using OWL and presented a process for a discrete part manufacturing case by providing OWL-based definitions for manufacturing service capability profiles and a description logic-based reasoning procedure [28]. Kjellberg et al. explored the possibility of modelling machine tool concepts defined in established industry standards using OWL language and discussed the mapping mechanism between ontology model and concepts in existing industry standards in detail [29]. Zhao et al. proposed a more systematic model for describing manufacturing equipment resources [30]. Until recently, a novel methodology to enable the development of a semantic model that supports DT creation for machine tools as well as other physical assets in a factory was developed on the basis of combination of ISO (International Organization for Standardization) 14649 and ISO 13399 standards [2]. These studies have successfully filled the gap that the industry needs an effective approach to virtualizing manufacturing resources.

2.2 Research gaps

The above literature has well suggested that complex physical objects in a factory such as machine tools can be virtualized in the cyberspace using ontology and OWL to support further DT creation. Nevertheless, to completely apply the DT concept in machining process, there are some challenges. Most of the latest research are focused on the DT creation in complex scenarios and no paper has mentioned how to model as-built process data of a machining part at present. As a result, there is a gap in terms of representing end-of-product lifecycle-related semantics [31]. How to model as-built process data in a simple and practical way still remains blank. Considering of the existing semantic modelling method in machining process, there is still a gap in terms of describing the “reality” of the specific domain [31]. Although some discussions about the DT creation of finished/semi-finished machining parts have been done, but all the critical concepts for modelling the as-built process data are still unclear and need to be analysed [32].

In conclusion, the information modelling of as-built process data is not comprehensive due to the lack of modelling method. The research on semantic modelling of as-built process data is becoming increasingly important. Besides, especially in a manufacturing plant, as-built process data stored in the e-documents or even paper documents are easily ignored because more attention is paid to the qualification rate when machining parts are delivered. Therefore, there is a strong need to provide proper tools that support a manufacturing company to conveniently model as-built process data. The following work was motivated to meet all the requirements above.

3. The proposed methodology

The as-built process information covers the data of multiple processes used to fabricate a machining part, including personnel, machine tools, cutting tools, material, process methods, and environment data needed to transform a raw material into a physical machining part. As mentioned in Section 2, DT creation means building a data model that encapsulates physical data and information relationship with its external environment. Hence, a rational and practical information model which encapsulates critical concepts and relationships of machining process is the technical core. Information modelling of as-built process data can connect the physical and virtual worlds and provide a systematic data structure and application logic.

Recently, Lu et al. pointed out that the most useful industry standards for developing product DT and production DT may be ISO 10303 (standard for the exchange of product model data, STEP), ISO 14649 (STEP-NC), ISO 13399, MTConnect (machine tools connect) and OPC UA (open platform communications unified architecture) [20]. A physical product can be abstracted with an information
model that represents its specifications of concern. Standard plays a valuable role in providing the information model. The as-built process data modelling approach proposed in this article is also inspired by the similar studies based on industry standards.

STEP-NC standard is developed to cover the current and expected future needs for data exchange, create an exchangeable and workpiece-oriented data model for CNC (computer numerical control) machine tools. STEP-NC is suitable for the information modelling of as-built process data because all the critical concepts and terminologies have been included and formalized. Meanwhile, STEP-NC is based on the “closed-world assumption” while the common ontology libraries are usually based on the “open-world assumption”. In a formal logic system for knowledge representation, the open-world assumption is the assumption that the truth value of a statement may be true regardless of it is known to be true or not. On the other hand, the closed-world assumption believes that any statement that is true is also known to be true [33]. This means that if the ontology modelling is only written in OWL without STEP/STEP-NC standards, there is no correct and authoritative way to model the domain and will be a lot of incomplete modelling content. To ensure the rigor and future scalability, the essential concepts and important terminology defined in EXPRESS schema are translated into OWL using OntoSTEP model in this article.

According to the discussion above, STEP-NC can provide the standardized framework for data modelling. As for information modelling, the common practice is to create a semantic model written in OWL because ontology methodology can provide the specific approach. Through ontology modelling, the internal concepts and relationships in machining process can be defined explicitly. The information modelling method of as-built process data is illustrated in the Fig.1. The modelling process includes four steps and the implementation details will also be presented in the Section 4.

Figure 1. The information modelling methodology.

**Step 1**: According to the seven-step method, the first step for creating an ontology is to consider reusing existing ontologies. However, there is no recommended ontology for the machining process data modelling at present. Considering the formalization and expandability, we decided to use some parts of STEP-NC to translate the related EXPRESS schema to an ontology written in OWL. As listed in Table.1, all the used STEP-NC parts written in EXPRESS are firstly merged into a combined schema file. The used contents are quite enough for the information modelling of as-built process data because STEP-NC standard has been revised several times by ISO and will be updated in the future. Hence, we merged all the relevant STEP-NC parts into a combined EXPRESS scheme, which consisted of Part 10, Part 11, Part 12, Part 111, Part 121, and Part 201.

| Part number | Title                              |
|-------------|------------------------------------|
| ISO 14649: 10 | General process data               |
| ISO 14649: 11 | Process data for milling           |
| ISO 14649: 12 | Process data for turning           |
| ISO 14649: 111 | Process data for turning          |
| ISO 14649: 121 | Process data for turning          |
| ISO 14649: 201 | Machine tool data for cutting process |
**Step 2:** Using the OntoSTEP plugin, the merged EXPRESS file is translated into the OWL schema in the Protege software automatically as shown in Fig.2. The defined entities and instances were successfully translated to OWL classes and individuals. The mapping of the basic concepts from EXPRESS to OWL is shown in Table.2. The complete methodology about the translation rules is available at [23].

![Figure 2. Screenshot of the translation.](image)

**Table 2.** Mapping of the basic concepts

| EXPRESS                      | OWL          |
|-----------------------------|--------------|
| Schema                      | Ontology     |
| Entity                      | Class        |
| Subtype of                  | Subclass of  |
| Attribute with an entity type| ObjectProperty |
| Attribute with a simple data type| DataProperty |

**Step 3:** In consideration of the simplicity of the implementation phase in Section 4, the OWL schema is manually trimmed to match the types of as-built process data that can be collected in the actual situation. Moreover, to record the additional data such as the temperature and humidity of the workshop, a superclass called “Environment” is then added because there is no description about the working environment in STEP-NC.

**Step 4:** Finally, the as-built process data are extracted from the e-document, which are generated by the manufacturing execution system (MES) and enterprise resource planning (ERP) system, and then manually adjusted according to the manually edited OWL schema. Using the Cellfie plugin built in the Protege software and the Manchester OWL Syntax [34], the as-built process data can be imported to the corresponding OWL classes in batches.

4. Case study

This section shows a case study using the proposed method to virtualize the as-built process data. The case study selected a typical machining part in an aviation manufacturing plant. The final result suggested that the proposed information modelling method and related tools are easy to use for modelling the as-built process data in the cyberspace. The remainder of this section details the process with an overview of the proposed ontology and how it can be used in the future.

A small subset of the ontology is presented as shown in Fig.3. In the generated ontology, all the concepts and terminologies inherited from the superclass Material, Method, Machine, and Person are translated from the merged STEP-NC EXPRESS schema. The object properties and data properties are not shown in the figure considering the readability. Also, to reflect the temperature and humidity of the workshop, we manually added the superclass “Environment”.

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To validate the proposed method, some as-built process data, which were collected in the aviation manufacturing plant, were selected to illustrate the effect in Fig. 4. The as-built process data were imported by the Cellfie plugin and the Manchester OWL Syntax. The raw data were adjusted manually and then recorded in Microsoft Excel documents due to the data security rules. For example, the relevant working steps to fabricate the test machining part (NPT-0001) were demonstrated in the figure. The type of the machining tool (GROB G350 machining center) used to fabricate the test machining part was also shown in the figure with its index number (No.2240180), location (the 17th workshop) and the other information.

5. Discussions

It is strongly suggested that the DT concept could improve the utilization of process knowledge in machining planning. Meanwhile, the process knowledge can be discovered by information modelling. From this point of view, the modelling approach to as-built process data of machining parts in this article emerges to be pivotal for applying the DT concept to the machining process.

The proposed ontology-based information modelling method enabled the case factory to model their as-built process data at the semantic level straightforwardly. The successful implementation was attributed to the reasonable and simple approach to modelling kinds of as-built process data. Further research with the case factory was found as a simple and standardized process because the data structure had been created with explicit machine-readable capability description using STEP-NC. Other feedback from the case factory suggested that more complete and human-friendly tools should be provided for creating the instances of the proposed ontology model.

6. Conclusion and future work

The application research of the DT concept is gradually deepening into all aspects such as designing, processing and maintenance. However, the development is still at a very early stage and how to model as-built process data under the guidance of the DT concept has not been effectively resolved at present. These circumstances are the biggest motivations leading to the presented study.

Firstly, the recent applications of semantic modelling using OWL oriented to DT were sorted out as well as the research gaps. The information modelling method was then explained in detail through

Figure 3. Subset of the as-built process data.

Figure 4. The demonstration of as-built process information.
figures and process demonstration. After the illustration and explanation of the proposed approach, a case study was undertaken to validate the method. Based on the feedback of the case company, the project in this paper provided a standardize information method of as-built process data. In a word, the most important contribution of the proposed methodology is its practicality in the modelling process, making it distinct and easy for companies to adopt. The ontology model can be extended with the development of new industry standards in the future.

All in all, the proposed research tried to fill the gap that the industry requires a practical way to enable companies to virtualize their as-built process data. As mentioned before, the abandoned as-built process data now can help engineers to perform evaluation and optimization by discovering the hidden knowledge. Thus, further research can potentially be done in the area of the interconnection of Protege, MES, and ERP. The attempts to merge full lifecycle product data should also be the focus of future research with the supports of new standards.

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