Axiomatic design based digital twin shop virtual reality fusion research

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Abstract. The digital twin workshop is a new mode of future workshop operation, which is of great significance to promote the smart manufacturing strategy. One of the keys to building a digital twin workshop is to realize the interconnection and integration of the information world and the physical world. At present, there are problems in the digital twin workshop such as difficulty in obtaining real-time data, difficulty in establishing twin models, and insufficient two-way real links between the physical and information worlds, which seriously affect the integration of reality and reality in the digital twin workshop. In this paper, with the goal of realizing the interconnection and co-integration of physical and information worlds in digital twin workshop, we use axiomatic design theory to systematically discuss the requirements and related key technologies for realizing the virtual-real co-integration of digital twin workshop, and obtain the hierarchical structure diagram of each component of digital twin workshop, which provides a reference for enterprises to practice digital twin workshop.

Keywords: Digital Twin Workshop; Axiomatic Design; Physical Information Co-integration.

1. Introduction

With the vigorous development of new generation information technology and advanced manufacturing technology, intelligent manufacturing has become the demand and trend of manufacturing development[1]. Various countries have put forward corresponding manufacturing development strategies, such as Germany's "Industry 4.0", China's "Made in China 2025" and Japan's "Connected Industry"[2]. The core idea of these strategies is to achieve the interconnection and integration of the physical world and the information world, so as to realize the intelligence of the production process[3].

Digital twin technology has great potential for application in manufacturing[4] . By establishing a high-fidelity model of physical entities, digital twin realizes bidirectional data interaction between physical entities and their virtual models, realizes continuous interaction and iterative evolution between physical entities and virtual models under the joint action of sensors and actuators, and realizes system operation optimization and decision making by relying on the real-time update of data from the physical world to its virtual models[5], which is a key technology to realize a new generation of intelligent manufacturing[6].

In recent years, with the application of digital twin in the workshop gradually formed digital twin workshop technology has been widely concerned by the manufacturing industry. Tao Fei et al[7]proposed the operation mechanism of digital twin workshop and the key technologies required for its implementation, and also proposed the five-dimensional model of digital twin workshop, on the basis of which, a lot of research has been conducted on the implementation method and modeling technology of digital twin; Zheng et al [8]explored the task-based workshop production scheduling method based on digital twin, which overcame the shortcomings of the traditional scheduling method with poor real-time response and large deviation from the actual production plan. Cheng et al [9]enhanced the dynamic scheduling performance of the production process by introducing digital twin-based machine tool behavior prediction, disturbance identification and evaluation methods; the application examples showed that the scheduling results using digital twin were better than those without digital twin in terms of maximum completion time, equipment utilization and task delay rate. Min[10] studied a shop floor scheduling method based on digital twin virtual-real interaction and virtual-real evolution, and developed a corresponding prototype system.

The interconnection and integration of the virtual world and the physical world is a key aspect of building a digital twin workshop. On the one hand, the digital twin workshop can realize real-time data-driven twin model update, so that the twin model and the physical entity can evolve together iteratively; on the other hand, it can obtain domain knowledge through data analysis and mining to promote the autonomous update and evolution of the digital twin, which makes the virtual workshop infinitely close to the actual production situation of the physical workshop. Based on the existing research results of digital twin, this paper explores the necessary conditions for the interconnection and integration of physical and virtual worlds in digital twin workshop with the guidance of axiomatic design theory, and promotes the fusion of heterogeneous elements in digital twin workshop, the fusion of multidimensional models in virtual workshop, the fusion of physical-information and data in workshop, and the fusion and application of workshop services. The aim is to promote the application of digital twin technology in the workshop production process.

2. Overview of digital twin workshop and axiomatic design

2.1 Digital Twin Workshop System Components

Digital twin workshop is a product of the times after the development of new generation information technology as well as manufacturing technology, which is a direction of intelligent workshop development. Compared with a single virtual workshop or digital workshop, digital twin workshop covers not only virtual workshop but also digital physical workshop. The digital twin workshop makes up for the shortcomings that the virtual workshop cannot collect real-time data and must express the workshop model through virtualization, while the digital twin technology can make effective use of data and realize the interaction and integration of physical world and information world through two-way real-time interaction and real mapping between physical workshop and twin workshop.

The system composition of digital twin workshop mainly includes physical workshop, virtual workshop, workshop twin data, workshop service system and the connection of each part, and its model structure is shown in Figure 1.

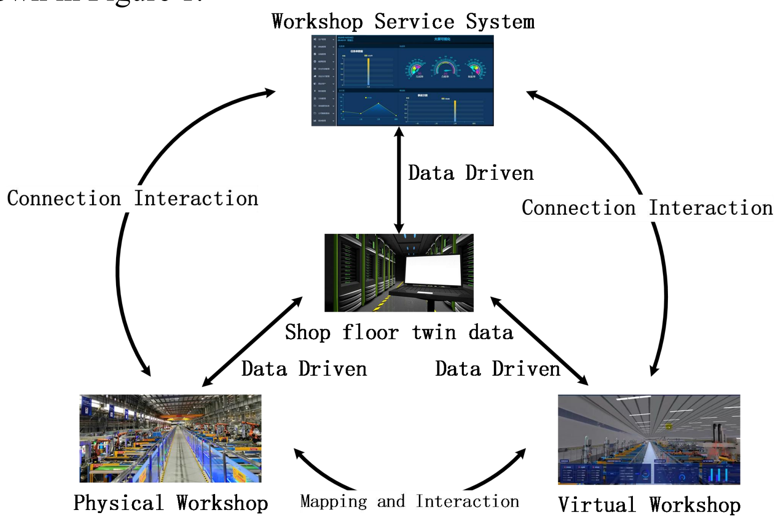

Fig.1 Digital Twin Workshop System Components

2.2 Axiomatic Design

Axiomatic design theory was proposed by Professor SUH in 1990, and is a summary of the basic principles and principles of design. Axiomatic design divides the design process into user domain, functional domain, physical domain and process domain, and the design process is to decompose these four domains layer by layer and iterative mapping, and the decomposition process follows the "zigzag" shape and follows independent axioms to maintain the independence of functional requirements. The application of axiomatic design theory can effectively reduce the complexity of the design and obtain a better design solution. The functional requirements of the product are mapped from the user's requirements, and the core part of the axiomatic design is the mapping from the functional domain to the structural domain, and the mapping process is expressed in equation (1).

$$\begin{Bmatrix} FR_1 \\ \vdots \\ FR_n \end{Bmatrix} = \begin{bmatrix} A_{11} & \cdots & A_{1n} \\ \vdots & \ddots & \vdots \\ A_{n1} & \cdots & A_{nm} \end{bmatrix} \begin{Bmatrix} DP_1 \\ \vdots \\ DP_m \end{Bmatrix} \#(1)$$

FR_n:Denotes the feature vector in the functional domain used to describe the extent to which the functionality implemented by the software meets its design specifications and satisfies user requirements.

DP_n:Denotes the feature vector in the physical domain used to describe the design parameters for achieving the functional requirements.

[A]:Denotes the design matrix, where the value of Anm indicates the degree of association between the nth feature and the mth design parameter, and when Anm=0 indicates that the two are unrelated.

In the whole design process, if the design matrix [A] is a diagonal matrix, any functional requirement depends on only one design parameter, then the design is called uncoupled design; if the design matrix [A] is a triangular matrix, a functional requirement depends on an appropriate sequence of design parameters, then the design is called decoupled design; otherwise any form of design matrix will lead to a coupled design, then it is necessary to change the functional requirement or design parameters to satisfy the independence axiom.

3. Axiomatic design process for the fusion of reality and imagination in the digital twin workshop

3.1 Digital twin workshop virtual-real fusion design requirement analysis

To achieve the goal of information-physical fusion in the digital twin workshop, we first need to solve the perception, collection and interaction of all kinds of production elements information in the physical workshop. However, the traditional workshop communication protocols and data interfaces of various types of production equipment are different, and the data formats are not uniform, so there are difficulties in data collection. At the same time, with the production activities, production task data, equipment operation data, etc. are increasing exponentially, which puts forward high requirements on the data storage capacity of the workshop.

The virtual workshop is essentially a collection of models corresponding to the production elements of the workshop, and the high-fidelity twin model is the basis for real mapping between the physical workshop and the virtual workshop in both directions. The virtual workshop relies on the accurate and effective digital twin model to simulate the production process, so as to evaluate the quality of the production plan and make timely adjustment and optimization if there are problems. At the same time, the production data accumulated in the virtual shop is constantly updated and contains a lot of domain knowledge, which can realize continuous control and optimization of the production operation process.

Data is the core support of the digital twin. The workshop environment is complex and the production elements are diverse, so the workshop data has big data characteristics such as large scale, multi-source heterogeneity and time-varying. Through workshop data, we can establish the mapping between production process and operation decision, realistically simulate the workshop production operation state, and perform a series of operations such as collecting, filtering, correlation, mining, iteration and fusion on workshop data to obtain the domain knowledge of workshop production, improve workshop production efficiency and product quality, reduce workshop energy consumption, and ensure workshop equipment health, etc.

The workshop achieves the goals of intelligent production, precise control and intelligent operation and maintenance, which is essentially a series of complex dynamic intelligent decision-making problems. Due to various factors such as complex and changing production environment, random disturbance events, fuzzy production factors and changing production tasks, the related decision-making problems are highly complex and dynamic. The workshop service system is an important link to realize the interconnection and integration of the physical world and the information world, and the application of twin data to drive the intelligent scheduling, production process control, equipment monitoring, production optimization and other functions of the workshop is the ultimate goal of building a digital twin workshop.

Based on the above analysis, the total functional requirements {FR} are decomposed by using the "zigzag" mapping method to obtain the functional requirements FRs and then transform them into design parameters {DP}. The functional requirements {FR} and design parameters {DP} are decomposed at the first level in the following.

(1) Functional requirements {FR} first level decomposition

FR_1: Physical workshop element fusion.

FR_2: Virtual workshop multidimensional model fusion.

FR_3: Workshop twin data fusion.

FR_4: Workshop service fusion.

(2) The first level decomposition of design parameters {DP}

DP_1: intelligent sensing and interconnection of workshop heterogeneous production elements.

DP_2: bi-directional real mapping of physical and virtual workshops.

DP_3: complex data classification modeling and dynamic analysis evolution.

DP_4: Data-driven workshop service mechanism.

The first level design equation is as in equation (2).

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \end{Bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ X & 0 & X & 0 \\ 0 & X & 0 & X \end{bmatrix} \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \end{Bmatrix} \#(2)$$

3.2 Functional-Architectural Model for Information-Physical Fusion in the Digital Twin Workshop

Axiomatic design second layer FRs decomposition is to determine the functional requirements that can satisfy the first layer design parameters under the consideration of the first layer design parameters, and then determine the design parameters according to the functional requirements obtained from the decomposition. For DP_1 workshop heterogeneous production elements intelligent sensing and interconnection, the functional requirements obtained by decomposition are four functions of workshop data sensing and collection, data transmission and integration, equipment interaction and control, intelligent collaboration and co-integration; for DP_2 two-way real mapping of physical workshop and virtual workshop, the functional requirements obtained by decomposition are multidimensional model construction, model evaluation and validation, multidimensional model association and mapping; for DP_3 complex data classification modeling and dynamic analysis evolution, the functional requirements obtained from the decomposition are data modeling and cleaning, data association and mining, data iterative evolution and fusion; for DP_4 data-driven workshop service mechanism, the functional requirements obtained from the decomposition are twin data to workshop service conversion, workshop intelligent management and optimization, workshop service collaboration and fusion. The second layer FRs decomposition and its DPs mapping are shown in Table 1.

Table 1. Functional requirement decomposition and parameter mapping

Functional Requirements Domain	Function Description	Design parameter field	Parameter Description
FR_{11}	Shop floor data sensing and acquisition	DP_{11}	Development of data acquisition equipment and technology
FR_{12}	Data Transfer and Integration	DP_{11}	Unified data protocols and device interfaces
FR_{13}	Device interaction and control	DP_{11}	Dynamic interactive real-time control method
FR_{14}	Intelligent Collaboration and Inclusion	DP_{11}	Virtual Reality and Augmented Reality Technology
FR_{21}	Multidimensional model construction	DP_{21}	Physical entity geometry, physics, behavior, rule inscription
FR_{22}	Model evaluation and validation	DP_{22}	Build accurate assessment and validation methods
FR_{23}	Multidimensional model association and mapping	DP_{23}	Establishing the association between models
FR_{31}	Data Modeling and Cleaning	DP_{31}	Multidisciplinary, multi-physical quantity and multi-scale data processing methods
FR_{32}	Data Correlation and Mining	DP_{32}	Information Clustering and Feature Extraction
FR_{33}	Data Iterative Evolution and Fusion	DP_{33}	Shop floor data evolution and statistical characterization
FR_{41}	Twin data to shop floor services conversion	DP_{41}	Improve relevant theoretical and methodological research
FR_{42}	Intelligent management and optimization of the workshop	DP_{42}	Research on intelligent management methods
FR_{43}	Shop floor service collaboration and integration	DP_{43}	Service collaboration strategies and theories

3.3 Functional-structural decomposition results

The functional requirements decomposition diagram for the information-physical fusion of the digital twin shop is obtained by decomposition level by level, as shown in Figure 2.

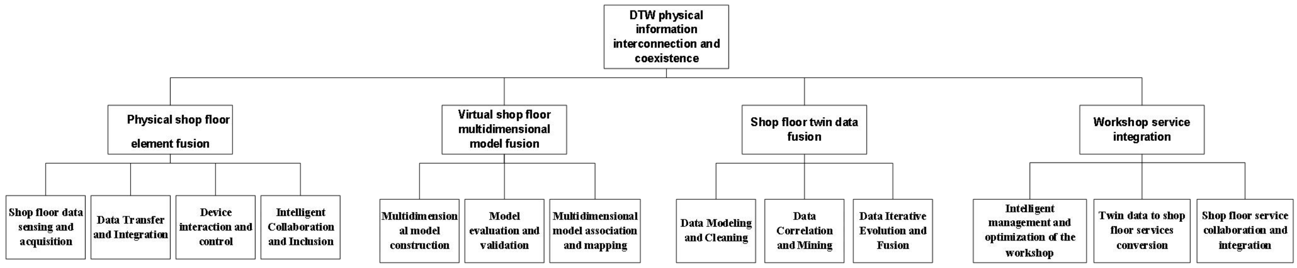

Fig. 2 Functional requirements breakdown diagram

The design matrix [A] obtained by the 1st level decomposition is a lower triangular matrix, such a design is decoupled and satisfies the independence axiom， among them, FR_3 is interrelated with

DP_1 and DP_3, so its design structure needs to follow certain rules. The functional requirements and design structure influence matrix obtained from the decomposition of layer 2 is shown in Table 2. It can be seen that the influence matrix as a whole is a lower triangular matrix, which satisfies the axiom of independence, where the functions FR_{13}, FR_{21}, FR_{23}, FR_{31}, FR_{33} and FR_{43} are related to their corresponding structures, so their design structures should also follow certain laws.

Table 2. Functional requirements and design structure impact matrix

	DP_{11}	DP_{12}	DP_{13}	DP_{14}	DP_{21}	DP_{22}	DP_{23}	DP_{31}	DP_{32}	DP_{33}	DP_{41}	DP_{42}	DP_{43}
FR_{11}	X	0	0	0	0	0	0	0	0	0	0	0	0
FR_{12}	0	X	0	0	0	0	0	0	0	0	0	0	0
FR_{13}	X	0	X	0	0	0	0	0	0	0	0	0	0
FR_{14}	0	0	0	X	0	0	0	0	0	0	0	0	0
FR_{21}	0	X	0	0	X	0	0	0	0	0	0	0	0
FR_{22}	0	0	0	0	0	X	0	0	0	0	0	0	0
FR_{23}	X	0	0	0	0	0	X	0	0	0	0	0	0
FR_{31}	0	0	X	0	0	0	0	X	0	0	0	0	0
FR_{32}	0	0	0	0	0	0	0	0	X	0	0	0	0
FR_{33}	0	0	0	0	X	X	0	0	0	X	0	0	0
FR_{41}	0	0	X	0	X	0	0	0	0	0	X	0	0
FR_{42}	0	0	X	0	0	0	X	0	0	X	0	X	0
FR_{43}	X	0	X	0	0	X	0	0	X	0	0	0	X

4. Summary

As one of the new models of future workshop operation, the digital twin workshop has great potential to promote the realization of intelligent manufacturing. This paper addresses the key issue of interconnection and co-integration between the physical world and the information world of the digital twin workshop, and explores the interrelationship of workshop production factor perception and interconnection, virtual model fusion, workshop data co-integration to, and workshop service fusion application as well as the corresponding key enabling technologies with the guidance of axiomatic design theory, which provides some guidance for the practical application of digital twin in the workshop.

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