Conceptual Design of Intelligent Manufacturing Equipment Based on a Multi-source Heterogeneous Requirement Mapping Method

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Abstract: Intelligent manufacturing equipment constitutes important prerequisite and foundation for processing and manufacturing. In its conceptual design process, functional determination based on customer needs (CAs), intelligence demands (IDs) and manufacture constraints (MCs) is the prerequisite and basis for subsequent design work. As these various requirement information becomes more complex and mixed, a practical design method will improve the design efficiency of this type of problem. Although research on requirement acquisition and transformation methods has been intensively studied, this problem is still difficult to solve by traditional methods due to the multi-source heterogeneous characteristics of requirement information. To overcome this problem, a requirements mapping methodology is proposed to decompose and transform multi-source heterogeneous requirements and map them to different functional knowledge (FK). Multi-source design requirements are categorized by different objectives such as manufacturing, customer, and intelligence, and these heterogeneous information is analyzed by the decomposition method corresponding to them. The conceptual scheme (CS) is derived through a four-step selection process: requirement set (RS) determination, FK mapping, knowledge combination, and scheme evaluation. The prototype design and an experimental study of a brand-new intelligent folding gantry crane is conducted. The results show that the proposed method can not only improve the design efficiency of intelligent manufacturing equipment, but also reduce the repetitive work in the detailed design stage.

1. INTRODUCTION

In recent years, the development of a new generation of information technology has brought new opportunities for industrial transformation to the manufacturing industry. As the foundation of the manufacturing industry, intelligent manufacturing equipment (IME) plays an important role in the transformation. IME refers to various types of manufacturing equipment with functions such as prediction, decision-making, control, and execution (Fu 2014), which mainly include high-end CNC machine tools, advanced assembly equipment, intelligent measurement and control devices, and so on. At present, the requirement for intelligent manufacturing equipment has become more accessible but also more complex due to the expansion of data (Wan 2018). Because in the conceptual design process of IME, not only the customer needs should be considered, but also the important information of the manufacturing process and the emerging intelligent demands should be put on an equal footing. And the information from a wide range of sources is often unstructured and irregular expression, which also brings challenges to the designer's work.

The researcher's goal is to establish a conceptual design framework based on the multi-source heterogeneous requirement mapping relationship, and generate a suitable design scheme based on the complex requirement information in the conceptual design stage. Under the guidance of this framework, multi-source design requirements are categorized by different objectives such as manufacturing, customer, and intelligence, so that various requirements and constraints are fully considered in the design stage. Through the mapping between requirements and functions, functions and functional knowledge (FK), multiple sets of alternative conceptual design schemes are formed. The framework adopts a multi-source heterogeneous requirement mapping method to improve the design efficiency of equipment and improve the degree of satisfaction of equipment to various requirements. Taking the conceptual design of intelligent folding gantry crane as an example, the feasibility of the proposed method is demonstrated.

2. RELATED WORK

2.1 Customized product concept design process

In order to enhance product innovation capabilities and shorten the design cycle, customized products have become the main development trend of the market (Liang, H. at al. 2004). The process of customized product conceptual design is the process of analysing functional requirements and generating product scheme (Zheng, H. 2018). Researchers have proposed some classical design methods such as empathic design and modular
design. Osório (2019) developed a method that will minimize the energy cost for a customized design of a quasi-stationary CPC-type collector. Zhang (2020) proposed a complex electromechanical system with a recursive inheritance mechanism to cope with the complexity of the system caused by increased requirement. In addition, our research team took a brand-new friction-wear testing machine (Guo, X. 2021a) and hard rock coring system (Guo, X. 2021b) as examples to study the conceptual design method of the product.

However, these related studies have not yet involved the research of intelligent manufacturing equipment, so it is still necessary to study the design methods of such important basic equipment.

2.2 Requirement analysis and transformation

In the era of big data the sources of information have become more numerous, which also increases the access to requirement. It is clear that requirement is not just from customers today, but is driven by multiple sources. Hellmuth (2020) studied the requirement from digital building models for factory building conversion. Chu (2016) proposed that manufacturing can be used as a tool to improve the design of equipment. In addition, our research team took a brand-new friction-wear testing machine (Guo, X. 2021a) and hard rock coring system (Guo, X. 2021b) as examples to study the conceptual design method of the product.

In addition, the requirements from different sources are often heterogeneous. To better exploit these requirements, Chen (2020) proposed a novel ontology-based requirement verification method to solve the problems; Wang (2019) integrate heterogeneous data sources into a holistic consideration in the proposed graph-based requirement acquisition framework.

Previously, the concept of multi-source heterogeneity was often found in the field of data information, but with the expansion of information, the requirement information has become complex and mixed. The analysis method of multi-source heterogeneous requirements in conceptual design should be further investigated.

3. FRAMEWORK

This paper proposes a requirement mapping method that supports IME conceptual design, which mainly includes four steps: requirement set (RS) determination, FK mapping, knowledge combination, and scheme evaluation. The framework of this method is shown in Fig. 1. In this framework, the conceptual design process starts with multi-source heterogeneous requirements and ends with conceptual scheme generation. A requirement decomposition rule is proposed, which provides a basis for decomposing complex requirements into requirement units. A transformation means is proposed to establish a mapping relationship between the structured expression RS and the function requirement (FR). Using the mutual combination of functional knowledge, multiple sets of conceptual design schemes are generated to meet the requirements. Finally, the dual evaluation criteria of economic index and technical index are adopted to select a more reasonable conceptual scheme. The framework refers to the FBS and Axiomatic Design (AD), forming a requirement-function-structure design process. On the basis of the method shown in Fig. 1, Section 4 explains the IME conceptual design process and method in detail through the introduction of principles and theory.

![Fig. 1. A requirement mapping framework for conceptual design](image-url)
4. METHODOLOGY

4.1 Multi-source requirement analysis

In the axiomatic design theory, the design process is divided into customer domain, functional domain, physical domain and process domain. The elements in the customer domain are customer needs/attributes, which are the needs of Customer. In view of the particularity of intelligent manufacturing equipment, we believe that in addition to customer needs, there are many other sources of requirement information, of which manufacture constraints and intelligence demands are extremely important (Fig. 2). The three types of requirement information need to be analysed in detail in order to provide basis and constraints in subsequent design tasks.

Customer needs (CAs): customer needs refer to the customer’s needs for intelligent manufacturing equipment in terms of function, performance, price and other aspects. This information directly comes from the customer, reflecting the object of design research and the problem to be solved, and it plays an important role in guiding the development, design and even the structure of the equipment (Sun 2020). The customer needs obtained in this paper are represented by a set of CAs, CAs = \{CA_1, CA_2, CA_3, ..., CA_n\}.

Intelligence demands (IDs): intelligence demands are the requirements put forward by customers for the intelligence of products. Kiritsis (2011) define intelligent products as systems with different intelligence levels that include functions such as sensing, memory, data processing, reasoning, and communication. That is to say, intelligence is mainly reflected in the imitation of human eyes, hands, brain and other functional organs by the product. Therefore, the demand for intelligence can be decomposed according to the level of intelligence, and the decomposition mode is relatively fixed. We expresses intelligence demands with set IDs, IDs = \{ID_1, ID_2, ID_3, ..., ID_n\}.

Manufacture constraints (MCs): manufacture constraints refer to the requirement information from the manufacturing side. As equipment for manufacturing other products, the design process of intelligent manufacturing equipment should have the materials, geometry and topology of manufacturing being considered (Würtenerberger 2018). Taking aero engine processing equipment as an example, aero engine components have many special and extreme requirements for processing equipment due to the characteristics of materials and structures, so these technical requirements should be considered in the conceptual design stage of processing equipment. We use set MCs to represent manufacture constraints, MCs = \{MC_1, MC_2, MC_3, ..., MC_n\}.

4.2 Conversion of heterogeneous requirement

In addition to having different sources, the requirements also have non-standard and unstructured characteristics. This paper refers to the concept of requirement unit proposed by Sheng (2015), and decomposes the requirements into the smallest unit that cannot be further subdivided. The decomposition process of heterogeneous requirements can be represented as:

\[ RS = \{RU_1, RU_2, RU_3, ..., RU_4\} \]

Where RU stands for requirement unit and RS denotes the requirement set consisting of requirement units. In order to effectively call the requirements information in the subsequent mapping process, the requirement unit is standardised and structured as:

\[ RU = \{id, type, objective, attributes\} \]  \hspace{1cm} (2)

In the above formula, id represents the index number of RU, type represents the type of RU, objective represents the object of the requirement information, and attributes represents the specific technical attributes. The formulation of RU decomposition rules refers to the independent axioms and information axioms of AD theory, and is improved according to the actual characteristics of intelligent manufacturing equipment.

1. Rule of Independence: The information carried between RUs should be independent of each other without interference.
2. Rule of minimum information: requirement should be divided into the smallest unit that cannot be further subdivided, that is, the amount of information contained is the least.

3. Rule of similarity merging: Similar requirement units should be merged.

4. Rule of semantic consistency: RUs should correspond to requirements and be consistent with requirements in meaning.

In the mapping relationship between function requirement and functional knowledge.

4.3 Mapping between functional knowledge and functions

Functional knowledge describes the basic elements that are necessary to implementation of sub-functions. A single functional knowledge may be related to multiple function requirements, and the realization of some functions requires the collaboration of multiple functional knowledge. Therefore, there is a many-to-many mapping relationship between functional knowledge and function requirement (Fig. 4).

Set \( \{f_k_1, f_k_2, f_k_3, ..., f_k_n\} \) represents the functional knowledge FK, and set \( \{f_r_1, f_r_2, f_r_3, ..., f_r_n\} \) represents the decomposed equipment function requirement FR, then the mapping relationship between the functional knowledge and the function requirement can be expressed as follows:

\[
FR \rightarrow FK : (f_r_1, f_r_2, ..., f_r_n) = f_1(f_k_1, f_k_2, ..., f_k_n)
\] (3)

Since the constraints of manufacture requirements need to be considered in the mapping process, these constraints are expressed by the function \( f_2 \), and the mapping relationship can be expressed as:

\[
FR' \rightarrow FK' : (f'_r_1, f'_r_2, ..., f'_r_n) = f_2(f'_k_1, f'_k_2, ..., f'_k_n)
\] (4)

The different combinations of these functional knowledge can meet the function requirements in different realization forms, which makes intelligent manufacturing equipment have specific functions, structures and levels.

![Diagram of functional knowledge and function requirement mapping](image)

Fig. 4. Function requirements-functional knowledge many-to-many mapping process

4.4 Scheme evaluation

Since there are multiple combinations to achieve the design goals, this paper uses the technical index and economic index to score each scheme. A high economic index indicates that among the alternatives, this option is the most economical; a high technical index indicates that the alternative is the best technical option.

Assuming that there are \( n \) alternative design schemes, the technical index of scheme \( i \) is equal to the proportion of the technical score of this scheme in the total technical scores of all schemes:

\[
TI_i = \frac{S_{ti}}{\sum_{i=1}^{n} S_{ti}} \quad (i = 1, 2, ..., n)
\] (5)

The economic index of the scheme \( i \) is equal to the proportion of the economic score of this scheme in the total economic score of all schemes:
According to the classification of collection function, shown in Fig. 3.

detailed subspreads, the function is that the system has the characteristics of the flow branches and functional flow.

In order to reduce the complexity of the equipment, they are described by engineering language.

To establish through these correlations.

In the mapping process, these constraints are considered.

According to the mechanical analysis, the maximum stress value of the mechanism \( \sigma_2 = 286.42 \text{Mpa} \). Yield limit \( \sigma_e = \)
540Mpa. The maximum stress value is less than the manufacturing constraint, so the strength meets the requirements. The local extrusion stress $\sigma_2 = 63.1Mpa$, which is less than the manufacturing constraint 70MPa, which further verifies the reliability of the scheme.

6. CONCLUSIONS

Intelligent manufacturing equipment provides various tools and equipment for the industry. It is the cornerstone and cradle of the entire industrial system. As the requirements become more complex and mixed, it is necessary to study the multi-source heterogeneous requirement mapping method in the conceptual design process of IME. In the present study, a framework are proposed to support the conceptual design of IME, which are mainly divided into 4 steps: (1) requirement set determination, including the decomposition of multi-source requirements and the formatted expression of heterogeneous requirements. (2) FK mapping, when the requirements are converted to function requirements, match the appropriate functional knowledge for FR according to the mapping relationship. (3) FK combination, different functional knowledge combinations can produce multiple alternative design scheme. (4) scheme evaluation, according to economic index and technology index evaluates the alternatives and selects a scheme that is more suitable for the environment. To demonstrate its feasibility, a case study of a brand-new intelligent folding gantry crane is presented. Results have shown that this method can improve the efficiency of IME design. This method considers important manufacturing requirements in the conceptual design stage, and can reduce repetitive work in the detailed design stage. In addition, the establishment of the FK knowledge base and the iteration of the scheme are the future study goals.

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