Smart Design on the Flexible Gear based on Knowledge Graph

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Abstract. The design of a mechanical component, such as flexible gear, would require plenty of time and energy retrieval relevant design data, information, and knowledge to complete the design tasks. However, current design support tools can hardly assist this requirement. To fill this gap, this paper has proposed a smart design tool based on knowledge graph to intelligent recommend the possible design data, information, and knowledge to engineering designs to facilitate their design tasks and improve design efficiency. This smart design method includes three parts, creating knowledge representation model, constructing knowledge graph, and developing collaborative knowledge management system for implementation. The methodology is demonstrated in this paper with a case study on the design of a double-arc tooth profile flexible gear for a harmonic drive reducer. The results have shown the feasibility of the method, the improvement in the design efficiency through intelligent recommendation of design data, information, and knowledge.

1. Introduction
Harmonic drive reducer is a deceleration mechanism which uses deformed motion of flexible gear to transmit power or motion. Since it is of high precision, high rigidity, small size, large transmission ration, etc., it is widely used in industrial robots, aerospace devices and other mechanical equipment. As the core element of harmonic drive reducer, the design and development of flexible gear plays a key role on the accuracy and service life of the harmonic drive reducer. The profile of flexible gear is the fundamental feature which has various shape, e.g., circular, involute, S shape, double-arc shape, etc. Since different profile will affect the mechanical properties of the flexible gear, which type of profile should be used depending on working conditions and constrained. Normally, design engineer needs to spend a lot of time searching and determining these kinds of information, where a design support tool intelligently delivering required information can surely improve the design efficiency. Even though computer-aided design tools are widely used for such mechanical design, there is lack of a smart design tool can intelligently recommend useful data and information to designers based on their design context. To fill this gap, this paper proposes a smart design support tool that is based on knowledge graph to achieve this function, and a case study on designing a double-arc tooth profile flexible gear has been used to demonstrate the methodology and application of this smart design tool.

Engineering design is a complex process which will use a range of data, information, and knowledge. Engineering designers are normally spending a lot of time and energy search the data and information they required for their design tasks[1], [2]. Also, the design knowledge behind the data and information, i.e., the design rationale, are important for design decision-making [3]. Thus, a design support tool which can intelligently deliver the required data, information, and knowledge to them will be surely beneficial for them in undertaking design tasks and improving design efficiency. In the past decades, plenty of
computer-aided design tools are developed. However, they normally focus on the geometry modelling part, while the more recent Product Data Management (PDM) and Production Life Management (PLM) are more focus on organising the design data and information rather than directly dealing with design knowledge [4]. The reason for this is that they are lack of knowledge models for effectively capturing, exchanging, retrieving, and reusing design knowledge[5]. Thus, in this study, a novice design support tool based on knowledge capture and reuse has been proposed, using the increasing popular knowledge graph method [6], in order to achieve smart design through efficiently reusing previous design data, information and knowledge.

2. Methodology
The method to achieve smart design of flexible gear of harmonic drive reducer in this paper is through design knowledge acquisition and reuse, which includes three parts, i.e., creating knowledge representation model, constructing knowledge graph, and developing knowledge management system, as shown in Figure 1. Specifically, a knowledge representation model is firstly created to capture and represent the formal and tacit design knowledge generated during the design process of flexible gear. RFBSE model [7] is used to guide this process, which organises the design knowledge in terms of requirement, function, behaviour, structure and design evolution. Using this knowledge representation model, formal knowledge can be systematically organised in a tree structure. At the same time, the tacit design knowledge embedded in engineering designers' mind can be captured through the model in terms of know-what, know-how and know-why, where know-know describe the properties of the object, know-how explain the problem-solving process, and know-why reveals the design rationale. Based on this knowledge representation model, a knowledge graph can be built through a Neo4j graphic database. Each knowledge element can be recorded as the object in the graphic database, and they can be linked through the relation function. In this case, a structural knowledge network, i.e., knowledge graph is constructed. To perform as a design support tool, a web-based collaborative knowledge management system is required to, on the one hand, capture and represent the data, information and knowledge generated during the design process, and on the other hand, deliver the possible information and knowledge to the designers through intelligent recommendation.

3. Knowledge Acquisition and Representation
In this paper, a case study on a flexible gear of a harmonic drive reducer is used to demonstrate the proposed methodology. The first step to on capturing and representing the knowledge during the design process. There are various types of formal and informal knowledge generated during the engineering design process of the flexible gear. What type of design knowledge should be captured for reuse and how to structure them in a systematic way are the key issues to consider, where a knowledge representation model is needed. Based on the author's previous research, a RFBSE knowledge representation model is suitable for this mechanical engineering design. To be straightforward, a
structural decomposition on the harmonic drive reducer should be firstly done, where harmonic drive reducer includes three components, i.e., rigid gear, flexible gear and wave generator, showing the relationship between the flexible gear and harmonic drive. Further, a functional decomposition on these three components is undertaken, which not only describes the specific function of each component, but also obtains the embedded relation between each sub-function. Accordingly, the information and knowledge on the requirements and design evolution/iteration of these components can be further captured and represented. Figure 2 has shown the knowledge representation model capturing and representing the design knowledge of harmonic drive reducer.

![Functional Decomposition](image)

**Figure 2** Knowledge representation model of the harmonic drive reducer.

Based on the created knowledge representation model, a knowledge graph is created. In this paper, the knowledge on the flexible gear design is captured and stored using a Neo4j graphic database, as shown in Figure 3. Each piece of data, information and knowledge are represented in 'Nodes', and linked with 'Relation' lines. Since the flexible gear is a key component of harmonic drive, it is a 'Part node' linked with the harmonic drive reduce which is a 'Mechanism node' in the graphic database. A range of design knowledge are recorded using 'Element' nodes. For tacit knowledge, they are structured through 'What', 'How', and 'Why' nodes. In this case, a completed knowledge graph on the design of flexible gear design has been created for future knowledge reuse.
Based on the created knowledge graph, a Web-based Collaborative Knowledge Management System has been developed to reuse the design knowledge to achieve smart design, as shown in Figure 4.

4. Methodology
The knowledge graph and knowledge management system developed in the Section 3 includes the key design data, information and knowledge regarding to different types of flexible gear, which will be used in this section to implement smart design on a new flexible gear. In this case study, a double-arc tooth profile flexible gear is designed based on the previous design knowledge. Firstly, the basic tooth profile and schematic diagram of the flexible gear are obtained from knowledge graph, as shown in Figure 5.
The parameters shown in Figure 5 are linked to the 'Element' nodes in the knowledge graph. When the requirements on the flexible gear are determined, the design parameters are intelligently recommended, as shown in the table 1 and 2.

**Table 1  Design parameter of the harmonic drive reducer.**

| Symbol | Name                          | Values |
|--------|-------------------------------|--------|
| i      | Transmission ratio            | 100    |
| m      | Modulus                       | 0.5    |
| $Z_i$  | Number of teeth (flexible gear)| 200  |
| $Z_d$  | Number of teeth (rigid gear)  | 202    |
| $L/d$  | Length to diameter ratio      | 0.7    |
| $W_0^*$| Radial deformation coefficient| 1     |

**Table 2  Design parameter of the flexible gear.**

| Name                                      | Symbol | Formula                        | Values |
|-------------------------------------------|--------|--------------------------------|--------|
| Number of gear                            | $Z_r$  | $iu$                           | 200    |
| pitch circle                              | $d$    | $mZ_r$                         | 100    |
| Addendum circle                           | $d_a$  | $d + 2mh_a$                    | 100.94 |
| Dedendum circle                           | $d_f$  | $d - 2m(h_a + c)$              | 99.06  |
| Gear ring wall thickness                   | $\delta_1$ | $(0.1\sim0.3)$ $\delta$       | 0.3    |
| Smooth tube wall thickness                 | $\delta$ | $(0.01\sim0.015)$  $d$        | 1      |
| Soft round tube length                     | $L$    |                                | 67.725 |
| The soft wheel diameter                    | $d_r$  | $d_f - \delta - \delta_1$     | 96.75  |
| Gear ring width                            | $B$    | $(0.1\sim0.3)d$               | 15     |
| Transition fillet radius between barrel and bottom of cup | $R_3$  | $(3\sim4)\delta$              | 4      |
| Transition fillet between tooth ring front and barrel | $R_1$  | 0.002$d$                      | 0.2    |
| The back edge of the tooth ring and the cylinder body transition fillet | $R_2$  | 0.002$d$                      | 0.2    |
| Connect flange outer diameter              | $d_1$  | $(0.4\sim0.6)d$               | 50     |
| Flange diameter                            | $d_2$  | $0.5d_1$                      | 25     |
With these design parameters, a parametric design on the flexible gear is undertaken to create a 3D geometric model of the flexible gear by a Computer-aided design package, SolidWorks, as shown in Figure 6.

![Figure 6 Parametric design and automatic modelling in Solidworks.](image)

This 3D model has been further analysed using Finite Element Analysis in ANSYS to evaluate the feasibility of the design, as shown in Figure 7. The simulation results have shown that the mechanical properties of the designed flexible gear are feasible and meet the design goal.

![Figure 7 Finite Element Analysis on the 3D model of the flexible gear.](image)

5. Discussion and Conclusion
There are several ways to achieve smart design, and the method used in this paper is through knowledge capture and reuse. A knowledge representation model and knowledge graph are firstly created, based on which a collaborative knowledge management system is developed to perform as a smart design tool to intelligently recommend possible design data, information, and knowledge to generate a design scheme. In this case, it saves a lot of time and energy that engineering designers normally use to search data and information for their design tasks. Thus, the design efficiency has been improved in terms of information retrieval and the subsequent parametric design. The difficulty of this method is on the knowledge capture, which always requires plenty of time and energy in organising and recording the design data, information, and knowledge. To make this process more automatically can be the future work of this study.

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