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Ontology-based conceptual design for ultra-precision hydrostatic guideways with human–machine interaction

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ABSTRACT

This paper proposed a human–machine integrated conceptual design method based on ontology, aiming at eliminating the uncertainties and blindness during the design process of ultra-precision grinding machine, especially for its key component–the ultra-precision hydrostatic guideways. Both the required knowledge and the database of hydrostatic guideways are modelled using ontologies to provide a consensual understanding among collaborators. Moreover, a formalized knowledge searching interface is developed to obtain similar instances as references according to the design principles and rules. Based on the imaginal thinking theory, the search process and the results are attempted to be presented in the form of image in order to fit human's customary intuitive thinking frame, facilitating the decision making process. Finally, our design of hydrostatic guideways for an ultra-precision grinding machine is used to validate the effectiveness of the method.

1. Introduction

Conceptual design mainly aims at determining the working configuration from the requirements of products [1]. It is a highly complex and challenging task especially for complicated mechatronic products, such as large optical ultra-precision grinding machine [2]. Such a design task requires the interdisciplinary information to be considered simultaneously among collaborators, and this is a typical situation in enterprise information systems where techniques such as knowledge management, information integration, etc., would be involved [3]. Large optical ultra-precision grinding machine is the core equipment for astronomical mirror machining, which determines the efficiency of the whole process. In particular, amongst all the parts that constitute a large optical ultra-precision grinding machine, the performance of the guideways plays a key role, because it directly determines the axial accuracy of the machine base [4]. Up to present, although existent strategies [5] and successful cases [6] are abundant, the design of hydrostatic guideways extensively depends on the knowledge and experience of the designer, and a common knowledge base or design paradigm has not been completely formed yet. This situation has caused remarkable impedance for the efficient development of the product during the conceptual design phase [7], which is recognized as the most significant and creativity-requiring phase that has the dominating influence on the product quality [8]. If any fault occurs in this stage, the modifications in the later design processes would cause much unnecessary cost.

According to Tomiyama's point [9], design itself can be regarded as knowledge operation. This evidently demonstrates the close relationship between knowledge and design. Knowledge and information originate from different domains and exist in a diversity of forms, which may cause confusing situations where the same term holds different meanings, or the same concept is represented by different terms. This brings about big problems to teamwork based on knowledge exchange in conceptual design. Similar to the prevailing trend of searching through web or server to acquire knowledge, in order to efficiently and accurately using relevant knowledge, the best way might be establishing a general model for the domain knowledge and building a knowledge base through which the conceptual design is to be conducted. At this point, a noteworthy problem is that the definition or understanding toward a design problem in different design teams or different members within the same team are often heterogeneous or even distinct. To resolve this difficulty, ontology has been widely acknowledged and applied in design as an explicit formulation of a concept, because it provides the standard terminology, common vocabulary or formalized language [10,11] for some domain knowledge. In

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effect, ontologies have been developed for a variety of domains [12,13]. The advantages of using ontology for quick construction of design schema and easy-information-sharing platform have been demonstrated by many studies based on well-structured domain knowledge [14–16]. For example, Altuna specified configuration ontologies for products, which are further classified into component ontology, constraint ontology and requirement ontology. A knowledge-based tool for the specification of automotive systems is being developed through the application of ontology by Roy. Various methods and tools for ontology building are developed, such as Methontology [17], On-To-Knowledge [18], UPON [19], DILIGENT [20] and NEON [21], all of which have made tremendous contributions to the modeling of ontology in different levels of application.

In order to eliminate the blindness during the pivotal conceptual design, it is necessary to reuse knowledge to make this process more efficient, so that the holistic design lead time can be shortened. Viewing from this perspective, using ontology alone is not adequate, because the hierarchies it provides are limited in rather static or quasi-static descriptions. Symbiotically with ontology in philosophy, epistemology is concerned with the methodology for achieving and correctly understanding the knowledge used. In the realm of design science, it specifically addresses the question of what is the relation between the object of knowledge, e.g., the requirement and configuration of hydrostatic guideways, and guides the information flow during the process of design reasoning [8]. Therefore, epistemology has to be combined with the modeling of the dynamic consciousness or information streams, along with the cognitive process involved in the design ideation [22]. Moreover, human's experience and knowledge remain a necessity in decision-making and evaluation due to the intrinsic deficiency of computers. Thus, a human–machine interface is proposed based on imaginal thinking theory [23], which has provided a basis for unifying machine's logical thinking and human's intuitive thinking. As human thinking is accustomed to be based on images, which can also be easily processed by computers, this theory holds great merits in guiding the reasoning process to ease decision making.

The motivation of this paper is to propose an ontology-based conceptual design method for modeling the domain knowledge of ultra-precision hydrostatic guideways and establishing a general knowledge base acting as the platform for knowledge searching and standardizing the heterogeneous understanding during guideways design. Based on the imaginal thinking theory, we further propose that the search results and the guidance be presented in the form of images to facilitate decision making and concept visualization. The whole method is validated by our design case of an ultra-precision hydrostatic guidance.

2. Ontology-based conceptual design of ultra-precision hydrostatic guideways

2.1. Framework of ontological conceptual design

For the conceptual design of hydrostatic guideways, the primary task is to choose a suitable oil supply form, the restrictor type and the pad arrangement, which largely determine the fundamental performance of the guideways. Improving the design using existent instances as the reference is extremely important for enhancing the conceptual design efficiency and avoiding unnecessary or improper configuration. Finding existing configurations that satisfy current requirements is particularly important for novices. Thus, a conceptual design framework with a knowledge searching system is introduced as shown in Fig. 1. The knowledge searching method guides the building of the component selection system for the guideways design. The required input data for the guideways design from a design task, such as the load capacity, precision and stiffness, are specified by using the requirement ontologies. The knowledge searching system is established by design experts and engineers, and is modeled using membership functions analogous to those in fuzzy logics. Knowledge base of guideways is developed according to the guideways ontology composed of requirement ontology and configuration ontology, which is the consensual representation of guideways domain knowledge. Search keywords are defined, and corresponding weight factors are then assigned to them. Similarities among each search keywords are computed according to relevant design principles and rules, and then aggregated using the maximum method. It is noteworthy that the "keyword" in this paper holds a slightly different meaning from what is defined in database theory, because here the "keyword" is used as an entrance to the entire database for full text search, i.e., it leads the designer to the full details of an object that matches the features defined by these keywords. The result of the aggregation is used to obtain the instances most similar to the expected one for reference. Selection rules are applied using an imaginal interface for final decision making to get a proper configuration.

2.2. Ontological modeling for the conceptual design of hydrostatic guideways

2.2.1. Brief introduction of hydrostatic guideways

In simple words, hydrostatic guideways operate under the mechanism of hydrostatic lubrication and support [24], which forms an extremely thin fluid lubrication film between two relatively moving support surfaces by using an external pressure source. A typical structure of hydrostatic guideways is shown in Fig. 2(a). Compared to traditional rolling contact guideways and aerostatic guideways, hydrostatic guideways own the following advantages:

- Almost no wear, the expected life of the kinematic pair is very long, thus the long-term fabrication precision can be maintained.
- Extremely low friction, so the drive power can be greatly reduced.
- The thickness of the oil film is highly stable, no crawling would appear even at very low speed.
- The film has very high load capacity, stiffness and vibration absorbing ability, enhancing the motion accuracy.

Thereby, many of the most advanced ultra-precision machine tools (e.g., Box [25], Freeform 705 G) have adopted hydrostatic guideways. Amongst all the parts of hydrostatic guideways, the most important task might be the design of oil pockets and pads (Fig. 2(b)), which determine the load capacity, thermal stability as well as the movement stability and accuracy. Besides, external support devices are indispensable, such as oil filtration system, pump, overflow valve, pressure gauge, and restrictor, etc.

2.2.2. Ontologies of the hydrostatic guideways for knowledge searching

Using an ontology as a unified and unambiguous representation and management of knowledge is critical to realizing the effective searching on a machine platform during the design. The ontology base contains the knowledge of different structures from various domains involved in the whole design process. According to the definition for design ontology proposed by Gero [26], we developed two types of top level ontologies for hydrostatic guideways: requirement ontology and configuration ontology, both of which can be decomposed into corresponding sub-level ontologies. During the conceptual design process, the requirements are specified by the indispensable search keywords, the application strategy of which is quite similar to the search of biological analogies as proposed by Shu in bio-inspired design [27]. Nevertheless, for the sake of an extensive search, requirement ontology is far from