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Automating design with intelligent human–machine integration

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ABSTRACT

This paper reviews the state-of-the-art methodologies for automating design with intelligent human–machine integration from the perspectives of ontology and epistemology. The human–machine integrated automating design paradigm is reviewed systematically based on a proposed prototype of human–machine integrated design, from the aspects of ontology-based knowledge management with local-to-global ontology transitions, and epistemology-based upward-spiral cognitive process of coupled design ideation. Particularly, imaginal thinking frame is proposed as the foundation of intelligent human–machine interaction that puts human and machine on an equal platform. Further, this paper presents implementations and applications of the automating design paradigm and concludes with the identification of future trend.

1. Introduction

1.1. Challenges

In the last century, the manufacturing industry has faced major challenges posed by the shifting from mass production to mass customization and personalization. Such challenges require the companies to be able to react to unpredictable, rapid and fluctuating market changes in a responsive and cost-effective way [205]. These dynamical market changes are driven by fierce global economic competition, better educated and more demanding customers, and a rapid advancement in processing technologies, which reflect a new balance among economy, technology and society [206]. Meanwhile, the past few decades have witnessed the evolution of manufacturing paradigm from Dedicated Manufacturing System (DMS) to Flexible Manufacturing System (FMS) [35]. Due to the high initial investment of FMS, other advanced manufacturing systems, such as Computer Integrated Manufacturing System (CIMS), Agile Manufacturing System (AMS), Reconfigurable Manufacturing System (RMS) [206] together with other Intelligent Manufacturing System (IMS) like Fractal, Holonic and Multi-Agent Manufacturing Systems have been developed. Although these manufacturing systems are explicitly different from each other according to the detailed comparisons in literature [103,117,177,205,206], they all share three basic characteristics, namely intelligentization, modularization and reconfigurability. Thus, nowadays companies not only should be flexible to process a variety of existing products, but also be scalable and reconfigurable to deal with new products in order to survive in the global competition. Major progress of product manufacturing has been achieved mainly through the development and application of advanced manufacturing technologies and tools [2,38,97,113,115,140,186,199].

While the advanced manufacturing systems and technologies mentioned above have provided some cost-effective solutions to mass customization and rapid responses to dynamic market changes, they are still inadequate in handling all the challenges, partly because of the fact that design science has come to a bottleneck and researchers often neglect the time needed for design of both new products and its manufacturing system. As shown in Fig. 1, in order to cope with the short window of opportunity for introducing new products, advanced manufacturing paradigms, technologies and processes mentioned above have dramatically helped to reduce the manufacturing system lead-time of the products during the last few decades, including the time for designing, building or reconfiguring the manufacturing system, as well as that for ramping up to full-volume and high quality production. However, the methodologies for designing both products and manufacturing systems are far from maturity, leading to the remaining long design time. While extensive attention has been paid to advanced manufacturing technologies, many other factors, including rather detrimental ones that could

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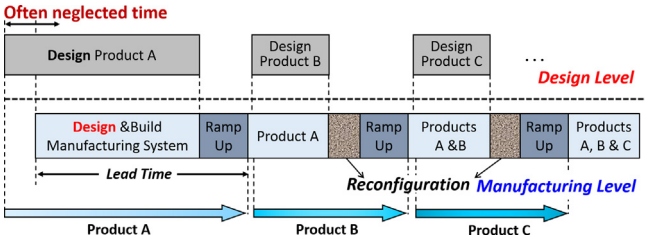

Fig. 1. The relationship between design and manufacturing.

affect the holistic product cycle are often neglected. It is conceivable that advanced manufacturing technologies or manufacturing systems alone can hardly address all the challenges. Design, which is usually regarded as the starting point or fountainhead of product manufacturing, determines what the product should be and where it is to be used and is the vital factor one should emphasize on. Unfortunately, although design theory and methodology have been quite well developed in the last few decades, they are still lagging behind the development of advanced manufacturing technologies and systems. In consequence, there are few or no corresponding design theories or methodologies (DTM) for product development and manufacturing processes. Without appropriate DTMs guiding how and where to use these modern technologies, the driving effect of advanced manufacturing systems will be largely limited. Therefore, despite of the manufacturing lead-time which has been shortened due to technology development, the design time of both new products and its manufacturing system has now become a dominant limiting factor. The application of advanced design technologies and tools in the early product design phase and the design of its manufacturing system are the situations where the most important decisions are made with respect to product functionality, quality, manufacturability, cost, environmental performance and life cycle for optimum design and development of products and manufacturing systems.

Furthermore, as the core of a manufacturing system, handmade and manually operated machines are being replaced by CNC, or automated equipment such as autonomous machine tools and robots. Therefore, the intelligentization of advanced manufacturing paradigms and machines has become an important trend, which necessitates artificial intelligence (AI)-based methodologies to realize the automation of the design paradigm.

1.2. Intelligent human–machine integration

In some sense, automating design using a computer can be regarded as a mimetic behaviour of human design activities, as computer systems are expected to independently finish the entire design process. Up to the present, despite numerous studies using AI for design to enable the computers to be equally effective as human decisions, few known systematic methods or scientific basis for automating design have been developed. With the rapid development of technologies like FEA for computer-aided design (CAD), computers, endowed with fast and massive computational and logical deduction abilities, are becoming increasingly more powerful for simple design tasks requiring fast and cost-effective performance. However, due to the intrinsic deficiency of computers in decision-making and evaluation, human participation remains a necessity for many complex tasks involving qualitative judgements and uncertainties. In contrast, humans tend to practise intuitive thinking based on their rich experience and knowledge, while compared with computers, humans are much weaker and slower at logical deduction. Therefore, human–machine integration is a promising approach for automating design, combining the quantitative computation and qualitative analytical advantages of both while compensating the weaknesses of each other.

While it is well recognized that human–machine integration should surpass the power of either human or machine intelligence alone, advances in harmonizing the intelligent interaction between human and machine have been slow, partly because of the gap between human's customary intuitive thinking and computer's logical thinking under the traditional AI framework. Recently, the imaginal thinking method [207,209] has attempted to narrow this gap. This method considers imaginal thinking, the synonym of image-based thinking, to be the fundamental mode of human thinking. It is defined as the forming of images and the holistic and direct comparisons among them. Moreover, imaginal thinking is supported by experimental psychologists [19] who have shown that people actually use images, not descriptions as computers do, to understand and respond to the outside world. Brooks' [19,20] achievements in action-based AI theory also show indirect evidence of human imaginal thinking, which is different in approach but equally satisfactory in result. Thus, imaginal thinking is helpful to promoting automating design with intelligent human–machine interaction, because design ideation can be considered as the generation and transformation of generalized images.

On the other hand, research [207,209] has proven the feasibility of computer's behavioural intelligence in mimicking human imaginal thinking. The emergence and rapid development of 3D modelling in CAD have seen the increasing ability of computers in processing images. Moreover, virtual reality (VR) [3,112] and augmented reality (AR) technologies [121] have been exploited as powerful human–machine interaction tools by creating efficient interactive environments. Although technology developments have laid a firm foundation, the current AI level is still the most influential limiting factor to the implementation of automating design paradigm. Therefore, for situations where computer systems alone are inadequate to complete the design tasks, the guidelines based on imaginal thinking can help to build up an automating design paradigm with intelligent human–machine integration technologies, such as 3D images under a VR or AR platform.

1.3. Automating design based on ontology and epistemology

It has been well recognized that design is essentially an iterative process based on human experience, knowledge and creativity, indicating that human's intuitive creativity is vital for coming up with a brand-new design solution, while AI and existing design theories fall short to generate a general framework. Due to the fact that the nature of human intelligence has not been fully discovered and confusion still exists between the intelligence of human design and the intelligent nature of design itself, a clear definition of DTM has not yet been formulated. This further aggravates the relationships among individual theories and methodologies such that designers may feel difficult to choose a correct method to conduct design. Moreover, the application of AI becomes essential as required by the ultimate goal of automating design. This puts forward higher requirements on the understanding of the inherent relation between the intelligence of human design and the intelligent nature of design, and the logical mapping to AI is even more profound. Thus intractable problems arise when complex connections among the intelligent nature of design, human intelligence and AI need to be resolved.

Examining these problems from a higher perspective with broader and deeper insights helps greatly in eliminating the confusions. Philosophical views of design [86], which are concerned with the explanation of the fundamental nature of existence and the relationship between human and external knowledge, have been dedicated to building the ultimate guideline for the understanding of design. Actually all the design activities performed by human also act as a significant means of obtaining knowledge. Two topics, namely ontology and epistemology have been leading philosophical research. Ontology is defined as the science of things that exist, including the nature, the properties, the characters and the relations of the objects in reality [69,70]. Epistemology, on the other hand, is concerned with the methodology for achieving and correctly understanding the knowledge. In the realm of design science, it

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