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Artificial Intelligence in Design: An Overview

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We are pleased to report that this JCISE special issue on Artificial Intelligence (AI) in Design attracted about forty submissions with more than a hundred coauthors! These numbers speak volumes about the importance and vigor of AI in Design as an interdisciplinary field of study. We hope that this special issue will add to the momentum of research into AI in Design.

Since these numbers were larger than we expected, we requested the JCISE Editor for help in managing the reviewing of the submitted papers. As Guest Editors of this special issue, we managed the reviewing about twenty five submissions that focused on knowledge-based design. The JCISE Editor and Associate Editors managed the reviews of other submissions. The twenty five or so submissions in knowledge-based design were reviewed (and many re-reviewed) by close to seventy five reviewers over several months. The fourteen papers included in this special issue represent the result of this long, deliberative process. A few other papers submitted to the special issue will soon appear in regular issues of JCISE.

Research into knowledge-based design attends to several closely related issues that we may classify into seven categories: (1) uses of knowledge in design, (2) content and representation of knowledge, (3) organization and access of knowledge in memory, (4) acquisition and learning of knowledge, (5) communication of knowledge in human-computer interaction, (6) communication of knowledge in human-computer-human collaboration, and (7) methodologies for studying knowledge-based design. Briefly, use of knowledge pertains to design tasks and methods, such as the method of case-based reasoning for the task of proposing a conceptual design and the method of model-based reasoning for adapting a proposed design to meet specific design requirements. Content of knowledge refers to the types and ontologies of knowledge, for example, knowledge of specific kinds of objects, variables, concepts, relations, processes, etc. Representation of knowledge refers to forms of knowledge such as logical predicates and production rules, frames and schemas, drawings and diagrams, etc. The uses, contents and representations of knowledge appears to be the focus of most research on knowledge-based design.

However, knowledge in general is useful only insofar as it can be acquired when feasible and accessed when needed. This raises the issues of learning and memory, which thus far appear to have received relatively little attention in research on knowledge-based design. Topics in memory cover a large range, including issues such as use of conceptual graphs and discrimination trees to organize design cases, and use of functions as indices to the structural components and causal behaviors of a design. Topics in learning too cover a vast landscape, including issues such as learning of functional indices to design cases, learning of design patterns and principles from design cases, and learning of functional models of designs from their drawings.

Design of course is situated in an external world. In modern design, designers in general generate designs through interaction with computers on one hand, and in collaboration with other designers on the other. Collaboration among designers in contemporary desgn again is mediated through computers. This raises the issue of communication of design knowledge in human-computer interaction, for example, through diagrams, design models, and virtual and augmented reality. It also raises the issue of communication in human-computer-human collaboration, for example, through design repositories, design models, and design rationale. Research into knowledge-based design has sought to address both kinds of design communication.

Finally, research on knowledge-based design addresses methodological issues such as the empirical basis and epistemological foundations of design theories, and measures and metrics for evaluating design techniques and decisions. Methodological topics in knowledge-based design include set- and graph-theoretic characterization of classes of design problems, axiomatization of design knowledge, protocol and *in situ* studies of designers, and construction of standardized datasets for evaluating the efficacy of design methods.

Papers in this Special Issue

Ten of the fourteen papers in this special issue can be classified into three main categories: (i) functional decompositions of designs, (2) evolutionary computing in design, and (3) communication of design knowledge. Since function is a core idea in engineering design [1,2], functional representations and their use in design have received substantial attention in research into knowledge-based design. One class of functional models emphasizes behavior as an intermediate abstraction between function and structure, e.g. [3-8]. Following [1], four papers in this special issue focus on another class of functional representations that emphaize functional decomposition. In "Function Semantic Representation (FSR): A Rule-Based Ontology for Product Functions," Yang, Patil & Dutta present a rule-based ontological formalism for capturing functional descriptions of designs in order to more easily capture, exchange, and reuse them. In "A Constraint-Based Approach to the Composition Relation Management of a Product Class in Design," Yvars presents a constraint-satisfaction technique that takes into account structural and functional relationships in a product model for use in product dimensioning and configuring. In "Topological Information Content and Expressiveness of Function Models in Mechanical Design," Sen, Summers & Mocko deveop representations and metrics for analyzing the information content of function flow models of designs. Finally, in "Thesaurus for Natural-Language-Based Conceptual Design," Yamamoto, Taura, Ohashi & Yamamoto present a thesaurus based on semi-automatic extraction of the hierarchical structure of words from natural language sentences. They also show how the thesaurus can be used to simplify the process of functional decomposition in conceptual design.

Design in general is evolutionary in that new designs typically are generated not from scratch but by adapting and combining known designs. The evolutionary process of design has led many researchers in AI in design to explore methods of evolutionary computing, such as genetic algorithms and genetic programming, for evolving engineering designs, e.g., [9-11]. In knowledge-based design, the focus of this line of research typically has been on using domain knowledge to guide and constrain the evolutionary process. In "A System Framework with On-line Monitoring and Evaluation for Design Evolution of Engineering Systems," Gamage & de Silva describe a method for evolving engineering systems that uses bond graphs to represent designs and genetic programming to explore the design space autonomously. In "Case-Based Reasoning for Evolutionary MEMS Design," Cobb & Agogino present a case-based approach to providing a multi-objective genetic algorithm for synthesizing designs of Micro-Electro-Mechanical Systems.

As we briefly mentioned above, research on knowledge-based design includes communication of knowledge in human-computer-human collaboration. Construction of design repositories using multimodal knowledge representations is one powerful technique for communicating design knowledge, e.g., [12-19]. In "In Search of Design Inspiration: A Semantic-Based Approach," Setchi & Bouchard describe the use of domain-specific ontologies for semantic-based retrieval of design images. In "Impacting Designer Creativity Through IT-Enabled Concept Generation," English, Maim, Lewis, Schmidt, Viswanathan, Linsey, McAdams, Bishop, Campbell, Poppa, Stone & Orsborn describe design support tools for design repositories and concept generation.

Capture, storage and access of design rationale is another powerful technique for communication of design knowledge in human-computer-human collaboration, e.g., [20-24]. In "A Semantic Information Model for Capturing and Communicating Design Decisions," Rockwell, Grosse, Krishnamurty & Wileden describe the use of the Web Ontology Language (OWL) for representing and reusing design rationale. In "A New Design Rationale Representation Model for Rationale Mining," Liang, Liu, Kwong & Lee present a structured representation of design rationale that enhances automatic extraction of the rationale through data mining and knowledge discovery.

The last four papers in this special issue signify the large and varied landscape of knowledge-based design. In "Hybrid Association Mining and Refinement for Affective Mapping in Emotional Design," Zhou, Jiao, Schaefer & Chen present a computational technique that combines association mining and refinement to map customer needs into design elements. In "Ontology-Based Multi-Platform Identification Method," Li, Chiang, Terpenny & Gilbert describe an ontology-based method to lower costs and cycle times when combining knowledge across design platforms in mass production scenarios. In "Transformation Design Theory: An Overview," Weaver, Wood & Jensen provide heuristics for transformation processes that take products or systems from one state to another in order to maximize their benefit and minimize trade-offs between conflicting needs. Finally, in "An Integrated Model of Designing," Srinivasan & Chakrabarti present a general model of design that integrates product- and process-related aspects of design based on protocol studies of designers in action.

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