Computer-Aided Design 44 (2012) 875–878

Contents lists available at SciVerse ScienceDirect

Computer-Aided Design

journal homepage: www.elsevier.com/locate/cad

Editorial

Fundamentals of next generation CAD/E systems

Since the 1960's, computers have been playing more and more important roles in engineering practices. The evolution of Computer-Aided Design and Engineering (CAD/E) systems has been driven by both the needs for efficient design processes and high quality representation of products, and the advancement of computing technologies and methodologies related to design practices. The computing (software) technologies that have greatly impacted on CAD/E systems include geometric modeling, finite element analysis, manufacturing process planning, human factor assessment and optimization algorithms, data base technologies, artificial intelligence, web search technologies, as well as networking and communication technologies. The paradigm behind current CAD/E systems can be characterized by the following features: (i) artifact geometry, structure and process modeling, (ii) displays-based graphical visualization, (iii) numeric data-based behavioral analysis and simulation, (iv) network-hosted remote collaboration, (v) data base-level functional integration, and (vi) product/process life cycle data management.

The market of commercial CAD/E systems is dominated by a number of large software developers who intend to offer complete solutions for the industry. Though academic research is still very active in the field of CAD/E systems, there are indications that the conventional system development resources will sooner and later become exhausted. A new paradigm might be necessary to provide additional support for the industry, to cope with the complexity of products, processes, and data/knowledge, and to open up new opportunities for researchers, innovators, system developers, system integrators, and end users. Many recent technological developments, for instance, smart and ubiquitous technologies, cloud computing, semantic web, cyber-physical systems, molecular computing, social networking and brain interfacing, are stimulating the discussions and the research towards a new paradigm.

This is the first of a series of special issues targeting the functionality, implementation, integration and application issues, approaches and solutions of next generation of CAD/E systems that will be used by designers and engineers around and after 2020. Special issues on Ubiquitous Computing-Based Design Tools and Systems and Application of Brain–Computer Interfaces in CAD/E Systems are already in development by other guest editors and authors. The objective is to explore new ideas, theories, methodologies, concepts, functionalities, forms of interaction, technologies and implementations that offer themselves to more efficient systems and applications. It is expected that novel information and knowledge mining technologies, mobile communication and ad hoc networking, semantic network technologies, air borne visualization technologies, smart reasoning and agent based computing, ubiquitous sensing and computing technologies, knowledge ontologies, natural interaction techniques will have a say in the formation of the paradigm of next generation CAD/E systems and environments.

The objective of this special issue is to provide an overview and to investigate the fundamental theories and techniques that may underlie the new paradigm. One major criterion that we applied at selecting the published papers was if they addressed one or more fundamental issues that might have a significant impact on future CAD/E systems. Based on the recommendation and review comments of the invited peer reviewers, out of twenty-one submissions, ten papers have been selected for publication in this special issue. Most of the submitted papers have gone through three rounds of review. They address issues such as understanding, analysis, synthesis, representation, search and communication in computer aided design and engineering. The papers selected for this special issue can roughly be divided into three categories. The first category includes papers that concentrate on the understanding of design problems and design knowledge (including meaning based information search). The papers belonging to the second category deal with various different aspects of creative design synthesis, while those belonging to the third category address design expression and representation. They indicate a shift from product orientation to designer and environment orientation. Obviously, the contributed papers could cover only a part of this very complex and challenging problem, and raise many more fundamental questions than they could answer.

In the first paper, entitled "*Cognitive, collaborative, conceptual and creative — Four characteristics of the next generation of knowledge-based CAD systems: A study in biologically inspired design*", Goel et al. proposed four characteristics (referred to as four C's) for the next generation knowledge-based CAD systems. These systems are conceived to be supported by CAD technologies other than computational geometry and computer graphics. They argued that the next generation knowledge-based CAD systems will be (i) cognitive, (ii) collaborative, (iii) conceptual, and (iv) creative. The first C refers to a specific methodology for developing CAD systems, namely, grounding the design, development and deployment of CAD systems in cognitive studies; whereas the other three C's define the characteristics of design that CAD systems may support. The second C indicates that design is collaborative in at least four dimensions: (i) time; (ii) space; (iii) discipline; and (iv) culture. Communication between systems, between system and human, and between humans is the core for the collaborative process. The third C refers to conceptual design, which mainly focuses on the understanding of the design problem and the synthesizing of design information into solution concepts. The fourth C represents creativity, and indicates that the next generation of CAD systems will support design creativity and creative designs. Based on this framework and by using the SBF (Structure–Behavior–Function) model, the authors introduced in

doi:10.1016/j.cad.2012.05.005

details their design of a knowledge-based CAD tool, DANE (Design by Analogy to Nature Engine). From the observations that the authors made in their in situ cognitive studies, functional requirements for DANE were abstracted to support the process of biologically inspired design. The DANE was deployed and assessed in an undergraduate course on biologically inspired design taught at the Georgia Institute of Technology. The DANE system has been used as a case study for the four C's that the authors proposed in the paper. The authors' experiments have led to a major lesson: how to "teach" CAD systems for the necessary knowledge about the design, by developing a sufficient number of models as a reference resource for effective design. This "knowledge cost" is one of the fundamental problems that must be solved for the next generation CAD systems.

In an effort to support CAD systems to acquire knowledge from design experience, in their paper titled "*Grounded discovery of symbols as concept–language pairs*", Mukerjee and Dabbeeru aimed at creating viable computer vocabularies for design by training the system to learn the semantics through experiencing many designs in real world contexts. This research is based on an observation that it is only through the intensive exposure to real world designs that human designers have learned the structures underlying their knowledge system. To achieve this ambitious goal, the authors argue that it is necessary to conduct grounded learning of symbols by discovering patterns of functional viability based on a set of "good designs". It is claimed that candidates for initial design symbols are likely the information chunks that are constituted by the inter-relations of the design variables discovered and abstracted from functionally superior designs. Based on the initial semantics for design symbols, the authors show how the system can acquire labels by communicating with human designers. Different from most existing research, this research proposes to define a symbol as a {label, meaning} pair instead of representing a symbol merely as a label. The proposed symbol learning process addresses the following three questions: (i) which concepts are most relevant in a given domain, (ii) how to define the semantics of such symbols, and (ii) how to learn labels for these so as to form a grounded symbol. Obviously, many arguments presented in this paper are exploratory in nature; hence, the eventual viability of such an approach will require considerable more work. The questions revealed from this research may trigger future efforts in attacking this challenging yet significant problem.

While grounded symbols may imply a long way to the discovery of design knowledge from design experience, some researchers attempt to capture design rationale (DR) from design documents — a specific kind of design experience. In the paper, "*Learning the Whys: Discovering design rationale using text mining — An algorithm perspective*", Liang et al. aimed at developing approaches and algorithms to represent and extract effectively DR from unstructured design texts. The input of the algorithm is unstructured textual design documents, whereas the output is the DR represented by the ISAL (issue, solution, and artifact level) model. Firstly, the authors modeled sentence relationships through language patterns by defining a sentence graph. Afterwards, issue-bearing sentences, solution-bearing sentences, reason-bearing sentences, and artifact information are extracted with the help of the manifold-ranking algorithm and sentence graphs, respectively. Unlike existing approaches, their methods involved text mining, machine learning, information retrieval, and text processing techniques to enable automatic DR discovering. The authors demonstrated the process and the results of applying their algorithms for automatic retrieval and classification of information from patent documents. The preliminary results from this application provide insights for the automatic extraction of DR from industrial technical documents, design logs, emails, and design team wikis, which are much less unstructured.

One class of models to represent design knowledge is functional modeling, which includes function–behavior–structure, function–behavior–state, structure–behavior–function, and functional basis representations. One challenge to use those models, among others, originates in the fact that those models generally employ symbolic representations, whereas domain experts may often have to use parameter-level description to represent, design and analyze the designed artifact. In the paper "*A framework for computer-aided conceptual design system and its application to system architecting of mechatronics products*", Komoto and Tomiyama proposed a framework to combine both symbolic and parameter-level descriptions to represent the concept of a product in system architecting, where designers or system architects will divide, manage and integrate large-scale design problems across engineering domains. A product development framework is proposed with the focus on hierarchical system decomposition and consistency management of design information in the conceptual design. The framework supports modeling of design knowledge about function requirements and corresponding structural and behavioral realizations based on the Function–Behavior–State modeling. In this framework, the symbolic design knowledge in the conceptual design is acquired from discussions among system architects and domain experts who often use both symbolic terms (natural language) and parameter-level product models. A prototype CAD system was developed based on the framework to show how the proposed framework works.

Among various kinds of design knowledge, causal knowledge plays a critical role in the evaluation of design solutions, as well as in the identification of potential problems. In the paper titled "*DCR-based causal design knowledge evaluation method and system for future CAD applications*", Kim and Kim attempted to support new product design by developing a causal design knowledge systematization framework, knowledge evaluation method, and system. They present a new causal knowledge network evaluation method, where causality and network connectivity are used for the causal knowledge network with weighted vertices and weighted network connectivity for a network with weighted edges. To validate the proposed evaluation method, it has been compared with structural measures. The authors implemented the causal design knowledge evaluation system, KNOES, and tested it with a new valve design scenario. The authors argue that the causal knowledge networks should be properly evaluated and validated in order to integrate causal knowledge networks into the next generation of CAD systems.

In order to generate innovative design solutions, designers need to understand the design problems and search for high quality information relevant to the problem. Effective inquiry (that is asking the relevant questions) lies in the core of such understanding and searching processes. The paper, "*Model and algorithm for computer-aided inventive problem analysis*", contributed by Becattini et al., intends to support designers who do not know the TRIZ jargons and the TRIZ logic by developing a dialog based computer aided innovation system. The foundation of their approach includes the classification of problems according to their characteristics and the types of human cognitive strategies. The authors suggest that a necessary requirement to be considered for the next generation CAD systems is the capability to direct the thinking process of inexperienced designers in the early stages of design (that is, the formulation of design problem). In parallel to a series of research on question-based design, the dialogue-based system proposed by the authors deals with conceptual design stage. The paper demonstrates that through a dialogue-based interaction it is possible to guide the user towards a proper formulation of the problem statement, which is an essential step of any conceptual design activity. Although still at a prototype stage, the proposed software system has been tested with students at Politecnico di Milano and at the University of Florence. The paper details the structure of the algorithm and the results of the first validation activity. Afterward, it discusses the possibility to integrate the proposed approach into a new generation of CAD systems.

TRIZ application in particular and innovative design in general depends to a large extent on the search for potential design solutions from among existing technologies. Patent databases provide a rich source of technological information, if they can be used in an efficient and effective manner. Future CAD should provide several tools for designers to interact with patent databases, such as search functionality based on keyword(s); providing patent citation measures for a list of patents generated from searching; and facilitating design information extraction (functions, solutions, engineering conflicts, ontology, etc.). Designers could have multiple objectives in searching for design ideas in a patent database, such as means to satisfy specified functions, applications of particular structures or components, contradictions solved, or principles used for solving them. Regardless of the search objective and strategy employed, designers need to go through the search results to find high value patents. The assessment of level of invention (LOI) for a series of patents provides a useful input for screening and ranking patents to identify high-impact patents. However, the manual effort required for assigning LOI to each patent is laborious and time-consuming. In the paper "*A framework for automatic TRIZ level of invention estimation of patents using natural language processing, knowledge transfer and patent citation metrics*", Li et al. proposed a framework for classifying patents according to the level of invention, defined by the theory of inventive problem solving (TRIZ), which can be used as an approach for ranking patents according to impact. The framework is based on the hypothesis that knowledge flows together with backward citation measures can be extracted to characterize the inventiveness of an invention. The framework presented incorporated text mining of patents, natural language processing (part-of-speech tagging and hybrid stemming), and creation of knowledge-transfer metrics, and creation of machine learning models for classification of the patents into several categories of inventiveness, tested by stratified cross-validation and statistical hypothesis testing. The contributions of the paper are three fold. First, the proposed method provides a tool for innovators, designers, and patentees to identify innovative patents with the aid of information technology. Second, several new metrics for assessing the contribution of various knowledge sources in the creation of a new patented design idea were proposed and applied. The metrics assess the contributions of prior art having different degrees of technological distance from each other. Finally, the proposed hybrid stemming method achieved high accuracy for both patent documents and news articles.

For a long time, both the academia and the industry are seeking more natural manner for designers to finish design process under a low stress and highly effective state. A never ending effort in CAD systems is the expression and documentation of design ideas generated during the design process. In the paper "*Classification of primitive shapes using brain–computer interfaces*", Esfahani and Sundararajan introduced brain–user interface to CAD systems. The authors developed an algorithm that can distinguish primitive shapes (cube, sphere, cylinder, pyramid and cone) imagined by users. Experiments are conducted on 10 subjects and divided into three sessions. The first session uses image as cues, the second uses text as cues and the third includes images of complex objects as cues. The first and second session are repeated on 10 days to test the reliability/repeatability of the method. Brain signals are recorded by an EEG system from 14 locations on the scalp. Classification is done on the marginal spectra of four frequency bands (theta, alpha, beta and gamma) computed from the Hilbert spectrum of each independent component. The result shows an average accuracy of 44.6%. Although limited to primitive shapes, the work shows the promise of integrating brain computer interface into CAD systems. The integration will allow designers to naturally interact with the systems; thus, allow them to work efficiently and at the same time, maintain necessary flexibility for creative thinking.

Most of the existing CAD systems use Windows, Icons, Mouse, and Pointer, also called WIMP, as the main user interaction tools. Striving after developing a natural interface for CAD systems, in their paper entitled "*Conceptual design and modification of freeform surfaces using dual shape representation in augmented reality environments*"; Fuge et al. introduced a novel approach to exploring conceptual designs without traditional CAD surface operation such as trimming. They seek to help designers create and modify freeform surfaces through 3D hand gestures so that the designers do not need to be distracted by details of engineering design, such as edge boundary creation, surface trimming and so on. Consequently, the designers can conduct the conceptual design following a more natural and intuitive processes. Specifically, the authors explored multiple shape representations with varying uncertainty levels during 3D conceptual sketching as well as the algorithms for transformation between those representations. Their approach is more intuitive for deforming and exploring product shape in conceptual design stage. The main contributions of this work are: (i) the formulation of virtual shape data in multiple, concurrent representations (points and surfaces), and a regression method to transit fluidly back and forth between these representations during design, (ii) methods for deforming and exploring the product shape using these multiple representations, and (iii) representations of these forms such that designers can explore conceptual designs without the need for detailed surface operations such as trimming or continuity enforcement.

To support the top-down product design approach, which subdivides gradually and recursively a complex design work of a product into simpler design works of sub-modules, Chen et al. contributed their paper under the title "*Multi-level assembly model for top-down design of mechanical products*". They introduced a multi-level assembly model enabling to capture the important data and knowledge in design and to improve the productivity of product design. In particular, inheritance mechanisms are discussed to ensure the feasibility of information transferring and conversion between different design phases in the top-down assembly design process. However, the multi-level top-down design approach still requires the designer to deal with many constraint relations and dimensions in the early design stage. This research also presents other concerns worth further thought, such as combing the advantages of other approaches, including innovative and direct modeling. To enable next generation CAD tools to effectively support top-down design of products, a top-down assembly design process is refined from the traditional product design process to better exhibit the recursive-execution and structure-evolvement characteristics of product design. Based on the top-down assembly design process, a multi-level assembly model is put forward to capture the abstract information, skeleton information and detailed information involved. The multi-level assembly model is a meta-level implementation and is easy to be extended. Moreover, the inheritance mechanisms are explored to ensure the feasibility of information transferring and conversion between different design phases in the top-down assembly design process. A top-down assembly design sample is analyzed at length to show the application effects of the multi-level assembly model and the relevant inheritance mechanisms. In addition, a practical topic about the model adaptation of existing CAD systems is also discussed related to a broader application of the top-down assembly design.

Though this special issue covers a few critical issues for the next generation CAD/E systems, some fast evolving research streams such as ubiquitous and pervasive computing have not been addressed explicitly by the accepted papers. We envision that the future CAD/E systems will hinge on two fundamental pillars: the first is designers' mental model in the design process, particularly conceptual design process whereas the second include technologies supporting activities underlying the entire design process. In meeting business and social requirements on the future CAD/E systems, the results from these fundamental explorations will enable CAD/E industry to implement workflows that are aligned with the designers' mental model. As such, the designers' capability to achieve better creativity and productivity may be empowered by the CAD/E systems with the new paradigms grounded on those fundamentals.

We would like to take the opportunity to thank the authors for their valuable contributions and cooperation in responding to often rigorous reviewer comments through extended efforts to improve the quality of their papers. We must also thank our reviewers for patiently and carefully reading the submissions throughout many rounds of review and for their highly constructive feedbacks on the submissions.

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