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GUEST EDITORIAL

Biologically inspired design

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Natural processes have led to the development of a plethora of biological systems that carry out a multitude of tasks in a highly resource-effective manner within a variety of environments and constraints. Many of these tasks, environments, and constraints are similar to those relevant to engineering design. Therefore, biological systems offer a potentially rich source of inspiration for novel engineering designs.

There is ample anecdotal evidence of biological systems being used as inspiration for engineering. In the last few decades, research into developing biomimetic systems, which require a detailed understanding of biological phenomena with the goal of developing technologies that mimic such phenomena, has been steadily increased. Notable attempts include the development of bulletproof jackets by mimicking spiderwebs; robots that mimic various forms of natural movement such as those by fishes, leeches, and earthworms; and materials that mimic various properties of natural materials.

Biologically inspired designs have traditionally been an outcome of individual interest, accidental exposure, or systematic study. However, a better understanding of the process of biologically inspired design and supporting this process in a systematic manner to enable more effective and efficient biologically inspired engineering design is only beginning to gain momentum as an emerging area of active research and exploration. This Special Issue seeks to provide a state of the art collection of research outcomes in this area.

Although papers with artificial intelligence content were solicited, we broadened the scope to also include papers that provided knowledge and associated methodology for biologically inspired design. Suggested topics included, but were not limited to, the following:

- human-centered and computational models, techniques, or systems for (supporting) biologically inspired design (including biomimetics, biomimicry, and bionics);
- models of reasoning for biologically inspired design; and
- studies of reasoning for biologically inspired design.

This Special Issue contains five papers. The first paper, "Biological First Principles for Design Competence," by Andy Dong, focuses on the biological origin of design competence. This paper interprets the concept of biologically inspired design as the understanding of design competence from biological evidence. It reviews biological evidence from such diverse areas as evolution, genetics, and ethology from the perspective of design research to propose that design competence is the product of an evolutionary history during which five key competences in biological evolution developed: conception unbounded by sensory perception, symbolic manipulation at a level of secondary representation, theory of mind, curiosity, and mental time travel. Based on these five competences, the paper concludes by discussing how computation may provide a useful way to understand the origins and evolution of design competence.

The second paper, "A Content Account of Creative Analogies in Biologically Inspired Design," by Swaroop S. Vattam, Michael E. Helms, and Ashok K. Goel, takes biologically inspired design as an approach to design that espouses the adaptation of functions and mechanisms in biological sciences to solve engineering design problems. They argue that although biologically inspired design is inherently analogical in nature, current understanding of its analogical basis is relatively limited. The paper presents an observational study of a series of biologically inspired design sessions in terms of *why, what, how*, and *when* questions of analogy, which the authors argue would contribute toward developing a content theory of creative analogies in the context of biologically inspired design.

The third paper, "A Methodology for Supporting 'Transfer' in Biomimetic Design," by Julian Sartori, Ujjwal Pal, and Amaresh Chakrabarti, focuses on three issues. It develops a generic model of the biomimetic design process based on an analysis of various models espoused in the biomimetics literature. Based on an analysis of 20 biomimetic design cases, it identifies a generic set of levels of abstraction at which biomimetic transfer takes place. Finally, the paper presents a validated set of guidelines to encourage greater ideation fluency in the biomimetic design process.

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The fourth paper, "A Natural-Language Approach to Biomimetic Design," by L.H. Shu, summarizes various aspects of identifying and applying biological analogies in engineering design using a natural-language approach. In this approach, biological knowledge in natural-language format (e.g., books and papers) is searched for instances of keywords describing the engineering problem. Strategies for facilitating this search as well as how descriptions of biological phenomena are used in problem solving are summarized and demonstrated with several application case studies.

The fifth and final paper, "Function-Based, Biologically Inspired Concept Generation," by Jacquelyn K.S. Nagel, Robert L. Nagel, Robert B. Stone, and Daniel A. McAdams, presents a method for functionally representing biological systems through systematic design techniques to support conceptualization of biologically inspired engineering designs. Functional representation and abstraction techniques are utilized to translate biological systems into an engineering context to make biological system information accessible to engineering designers with varying biological knowledge. Two approaches to concept generation are discussed: using biological models to discover corresponding engineering components to mimic the biological system and using a repository of engineering and biological information to discover which biological components inspire functional solutions to fulfill engineering requirements.

These papers present a variety of perspectives. The paper by Dong focuses on the biological roots of design competence and argues design competence as an evolutionary trait. Taking the design research methodology framework of Blessing and Chakrabarti, research focused on design can be categorized into descriptive (i.e., *as is*) or prescriptive (i.e., *as should be*) studies. From this viewpoint, the first two papers are specifically focused on providing a descriptive view of biologically inspired design and the last two papers focus primarily on alternative prescriptive views of how to support ideation in biologically inspired design. The paper by Sartori et al. focuses on both: initially identifying an overall biomimetic process and the levels of abstraction at which "transfer: takes place (descriptive views) and then providing guidelines for supporting the biomimetic process (prescriptions).

Further, both the descriptive and prescriptive approaches nicely contrast with or complement one another. Vattam et al. use observational studies of designers to develop an overall biologically inspired design process, but Sartori et al. develop a generalized model based on a number of biomimetic design processes from the literature. Various categories of transfer are identified by Vattam et al., and various levels of abstraction of transfer are identified by Sartori et al.

Three approaches to support biologically inspired design are promulgated in the papers. Sartori et al. provide guidelines for the overall biomimetic design process, in particular focusing on the step of transfer. The works of Shu and Nagel et al. provide two contrasting approaches to identify analogous biological phenomena. Shu's work focuses on natural-language based approaches to search for relevant analogies in the existing literature, but Nagel et al. focus on structuring information extracted from the literature before searching on them for analogues. Both have their merits: the former requires undertaking neither the structuring effort nor the substantial effort of populating a database based on this structure. Effort is instead invested in identifying appropriate search strategies for locating meaningful information from a plethora of existing knowledge in the natural-language format; the latter requires investing substantial effort into prestructuring information, as well as the entry of a meaningful quantity of information in that structure, for the downstream benefits of easier and more focused search. Both can be potentially biased in how information is structured and searched or how search results are presented.

Several future directions for research have been suggested in the papers. Overall, we see enormous scope for new research to be carried out in this area in terms of developing better and more detailed understanding of the processes of biologically inspired design, in addition to potential alternative approaches to supporting these processes.

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