DANE: Fostering Creativity in and through Biologically Inspired Design

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Abstract. In this paper, we present an initial attempt at systemizing knowledge of biological systems from an engineering perspective. In particular, we describe an interactive knowledge-based design environment called DANE that uses the Structure-Behavior-Function (SBF) schema for capturing the functioning of biological systems. We present preliminary results from deploying DANE in an interdisciplinary class on biologically inspired design, indicating that designers found the SBF schema useful for conceptualizing complex systems.

Keywords: Design Creativity, Computational Design, Biologically Inspired Design, Biomimetic design

1 Introduction

Biologically inspired design uses analogies to biological systems to derive innovative solutions to difficult engineering problems (Benyus 1997; Vincent and Mann 2002). The paradigm attempts to leverage the billions of biological designs already existing in nature. Since biological designs often are robust, efficient, and multifunctional, the paradigm is rapidly gaining popularity with designers who need to produce innovative and/or environmentally sustainable designs. By now there is ample evidence that biologically inspired design has led to many innovative - novel, useful, sometimes even unexpected - designs (e.g., Bar-Cohen 2006; Bonser and Vincent 2007).

Despite its many successes, the practice of biologically inspired design is largely *ad hoc,* with little systematization of either biological knowledge from a design perspective or of the design processes of analogical retrieval of biological knowledge and transfer to engineering problems. Thus, a challenge in research on design creativity is how to transform the promising paradigm of biologically inspired design into a principled methodology. This is a major challenge because biology and engineering have very different perspectives, methods and languages.

We study biologically inspired design from the perspectives of artificial intelligence and cognitive science. From our perspective, analogy is a fundamental process of creativity and models are the basis of many analogies. Biologically inspired design is an almost ideal task for exploring and exploiting theories of modeling and model-based analogies.

We have previously conducted and documented *in situ* studies of biologically inspired design (Helms, Vattam, and Goel 2009). We have also analyzed extended projects in biologically inspired design (Vattam, Helms, and Goel 2009). In this paper we describe the development and deployment of an interactive knowledge-based design environment called DANE, which was informed by our earlier cognitive studies and that is intended to support biologically inspired design. DANE (for Design by Analogy to Nature Engine) provides access to a design case library containing Structure-Behavior-Function (SBF) models of biological and engineering systems. It also allows the designer to author SBF models of new systems and enter them into the library. We present initial results from deploying DANE in a senior-level class on biologically inspired design in which teams of engineers and biologists worked on extended design projects (Yen et al 2010). The preliminary results indicate that although we had developed DANE largely as a design library, in its current state of development, designers found DANE more useful as a tool for conceptualizing biological systems.

2 Related Work

Biologically inspired design as a design paradigm has recently attracted significant attention in research on design creativity, including conceptual analysis of biologically inspired design (e.g., Arciszewski and Cornell 2006; Lenau 2009; Lindermann and Gramann 2004), cognitive studies of biologically inspired design (e.g., Linsey, Markman and Woods 2008; Mak and Shu 2008), interactive knowledge-based design tools for supporting biologically inspired design (e.g., Chakrabarti et al. 2005, Sarkar and Chakrabarti 2008; Chiu and Shu 2007; Nagle et al. 2008), and courses on biologically inspired design (e.g., Bruck et al. 2007).

Our work on DANE shares three basic features of similar interactive design tools such as IDEA-INSPIRE (Chakrabarti et al. 2005, Sarkar and Chakrabarti 2008). Firstly, both IDEA-INSPIRE and DANE provide access to qualitative models of biological and engineering systems. Secondly, both IDEA-INSPIRE and DANE index and access the models of biological and engineering systems by their functions. Thirdly, both IDEA-INSPIRE and DANE use multimedia to present a model to the user including structured schema, text, photographs, diagrams, graphs, etc.

However, our work on DANE differs from IDEA-INSPIRE and similar tools in three fundamental characteristics. Firstly, the design and development of DANE is based on our analysis of in situ cognitive studies of biologically inspired design (Helms, Vattam, and Goel 2009; Vattam, Helms and Goel 2009). Secondly, insofar as we know, IDEA-INSPIRE has been tested only with focus groups in laboratory settings. In contrast, we have introduced DANE into a biologically inspired design classroom. This is important because from Dunbar (2001) we know that the analogy-making behavior of humans in naturalistic and laboratory settings is quite different: in general, humans make more, and more interesting, analogies in their natural environments. Thirdly, while IDEA-INSPIRE uses SAPPhIRE functional models of biological and engineering systems, DANE uses Structure-Behavior-Function (SBF) modeling (Goel, Rugaber and Vattam 2009). This is important because SBF models were developed in AI research on design to support automated analogical design (e.g., Bhatta and Goel 1996, Goel and Bhatta 2004). Thus, in the long term it should be possible to add automated inferences to DANE.

An SBF model of a complex system (1) specifies the structure, functions, and behaviors (i.e., the causal processes that result in the functions) of the system, (2) uses functions as indices to organize knowledge of behaviors and structures, (3) represents behavior as a series of states and state transitions that are annotated with causal explanations, (4) organizes the knowledge in $F \rightarrow B \rightarrow F \rightarrow B \rightarrow \ldots \rightarrow F(S)$ hierarchy, and (5) provides an ontology for representing structures, functions and behaviors. Other researchers have developed similar functional models e.g., Kitamura et al. 2004 and Umeda et al. 1996.

3 The Design By Analogy to Nature Engine

In the long term, DANE is intended to semi-automate analogical retrieval and transfer in biologically inspired design. Presently, DANE interactively facilitates biologically inspired design by (1) helping designers find biological systems that might be relevant to a given engineering design problem, (2) aiding designers in understanding the functioning of biological systems so that they can extract, abstract and transfer the appropriate biological design principles to engineering design problems, and (3) enabling designers to construct and refine SBF models of biological and engineering systems.

DANE employs a client-server architecture with a centralized design repository on the server-side. Each client is a thin client whereby all data is stored, updated, and recalled from the server. This architecture supports simultaneous access by multiple users and allows users to browse or edit the most current version of the repository.

DANE is a distributed Java application running on the Glassfish application server. Data is stored in a MySQL database, and we use EJB technology to handle persistence and connection pooling. Users access the application by going to a launch website that utilizes Java Web Start to both download and execute the application as well as apply any updates that have been made since the user last launched the application.

DANE's library of SBF models of biological and engineering systems is growing. In early fall of 2009, when we introduced the system into a biologically inspired design classroom, the library contained about forty (40) SBF models, including twenty two (22) "complete" models of biological systems and subsystems. The remaining were either SBF models of engineering systems or only partial models of biological systems. Biological systems in DANE were at several levels of scale from the sub-cellular to organ function to organism.

Systems are indexed by system-function pairs and retrieved by function name (e.g., "flamingo filter-feeds self"), by subject (e.g., "flamingo"), and/or by verb (e.g., "filter-feeds"). Function names often include additional specificity with regard to the objects upon which the function acts. In this case the flamingo is feeding itself. Upon selecting a system-function pair, users are presented with a multi-modal representation of the paired system-function (e.g. the "flamingo filter-feeds self" SBF model). For example, in DANE a system can be represented in text descriptions and images, as well as through visualizations of behavior and structure models. Example text and image modalities for the "flamingo filter-feeds self" model can be seen in Figure 1.

Briefly, this model describes how a flamingo uses its tongue to create negative pressure in its slightly open mouth to draw water in, closes its mouth, and then uses its tongue to force the water out through a filter-system composed of comb-like lamellae and