Biologically Inspired Design: Human Reasoning Using Nature's Experiences

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Abstract

Biologically inspired design uses biological systems as analogues for addressing design problems. We have conducted *in situ* observational studies of biologically inspired engineering design in practice. Based on these studies, we present a meta-analysis of biologically inspired design as extreme case-based reasoning. Case-based reasoning in biologically inspired design is extreme in that source domains of biological cases are unknown at the start of the process, the process of case retrieval has an intricate interplay with the process of problem decomposition, and case adaptation often entails run-time composition of partial solutions abstracted from multiple cases. Our meta-analysis of biologically inspired design suggests new challenges for research on reasoning from experiences.

Introduction

The popular cliché in design research "all design is redesign" has resonated with case-based reasoning because it suggests that the design of a new artifact must build on the knowledge of existing designs of a similar kind and must draw upon the experiences of designing similar artifacts. Design practitioners have applied the case-based paradigm for numerous classes of design problems in a variety of domains including architecture, computing, engineering. In their recent review of case-based design, Goel & Craw (2005) illustrate how every class of design problems provides unique challenges, and how every attempt to model and/or support a particular type of designing has required extending existing case-based reasoning systems in interesting ways, enriching our understanding of the case-based paradigm as a whole.

In this paper we consider biologically inspired (or biomimetic) design that uses biological systems as analogues for addressing design problems (Benyus 1997). We have conducted *in situ* observational studies of biologically inspired engineering design in practice. Based on these studies, we present a meta-analysis of biologically inspired design as extreme case-based reasoning. Case-based reasoning in biologically inspired design is extreme in that source biological cases are unknown to designers at the start of the process, the process of case retrieval has an intricate interplay with the process of problem decomposition, and case adaptation often entails run-time composition of partial solutions abstracted from multiple cases. The usefulness of our meta-analysis of extreme case-based reasoning in biologically inspired design lies in the set of research issues and themes it suggests.

Biologically inspired design

Biologically inspired design is an important, widespread and growing movement that espouses looking at nature for inspiration and potential solutions for solving design problems in various domains. In engineering in particular, adaptation of functions and mechanisms of biological systems has led to new and innovative designs in a variety of domains such as sensors, materials, mechanics and mechanical systems, robotics, computers and computing (Bar-Cohen 2006).

One goal of our research is to understand the cognitive processes of biologically inspired design with the aim of promoting it through the development of better design methodologies, educational techniques and computational tools. Our methodology employs *in situ* studies of design practices, processes and products of designers engaged in biologically inspired design. We have so far conducted three cognitive studies. The details of these studies can be found in (Helms, Vattam & Goel 2008; Vattam, Helms & Goel 2008). Here we briefly present three illustrative examples of biologically inspired design from our studies.

BriteView

The goal of the BriteView project was to design a display screen that was resistant to drowned illumination in bright sunlight and one that is power efficient. This problem was reframed, or "biologized," as: "How do organisms in nature generate bright, crisp colors even in the presence of bright sunlight?" From the reframed problem, designers found three biological sources of inspiration, Morpho butterfly wings, hummingbird (and duck) feathers, and peacock feathers. Based on the optical properties of each, an initial bio-inspired solution was created based on the

Morpho butterfly wings. This solution suggested creating a Christmas tree-like thin-film structure for each pixel that produced structural coloration through the interference effect (the butterfly wings are lined with such Christmas tree-like nano structures). Upon evaluation, designers felt that this solution was infeasible due to the complexity in manufacturing such intricate structures.

Designers chose the humming bird feathers as their next source of inspiration. Although the structural coloration produced by the humming bird feathers is based on the same optical principle as that of the butterfly wings, the hummingbird feathers contain a series of alternating layers of thin-films with different thickness instead of the intricate Christmas tree-like structure. Since simple layering of thin-films is more feasible to implement, this source was selected. At the same time this solution was being developed, designers also considered the structure of peacock feathers (the third source of inspiration). Any solution based on peacock feathers was quickly rejected because they had to contain multi-dimensional structure (as opposed to single-dimensional structure in both butterfly wings and humming bird feathers), which was considered even harder to implement.

Based on the humming bird feathers, the initial solution suggested that each pixel contain a two-layered thin-film structure, each layer having a different thickness. When they initially evaluated this solution, they realized that this solution did not give them the control to dynamically vary the color produced by the pixel, which was crucial for the design of the display. Then they revisited their earlier source of inspiration, the butterfly wing, because they knew that the color that the wing produced was determined by the length of the air-gap between the layers in the Christmas tree-like structures. Varying the length of this air-gap would vary the output color. Using this principle they modified their initial solution to include a gap between the two layers filled with air. Now they could move the bottom layer up and down mechanically changing the length of the air-gap between the two-layers, which in turn effected the color change in the pixel.

Figure 1 depicts the generation of this solution. Step 1 depicts the problem space early in the design. The overall function "design a display" has been decomposed and one of the sub-functions "generate bright color" has become the focus. Step 2 shows the initial solution generated based on the Morpho butterfly wings. This solution was evaluated and rejected. In Step 3 another trial design is generated based on the humming bird feathers. This is evaluated and a new function "control the reflected color" is added to the problem space. Step 4 shows the addition of this new function and an improved solution that integrated the idea of air gap (inspired by the butterfly wing design) into the trial design generated in Step 3.

Eye in the Sea

The goal of this project was to design an underwater microbot with locomotion modality that would ensure stealth. Designers approached this problem by biologizing it as: "how do marine animals stalk their prey or avoid predators without being detected?" Two marine biological systems were considered as sources of inspiration, copepod (a tiny, shrimp-like creature) and squid.

The initial research for the underwater microbot focused on the copepod as a source for understanding stealthy locomotion. In exploring this concept, designers became aware that the copepod used two rhythms of leg movement for achieving motion underwater: A slow and stealthy rhythm during foraging for food, and a quick but non-stealthy rhythm for escaping from predators. This understanding led the designers to decompose their original problem into two separate functions, one for slow movement, and one for rapid, yet stealthy movement.

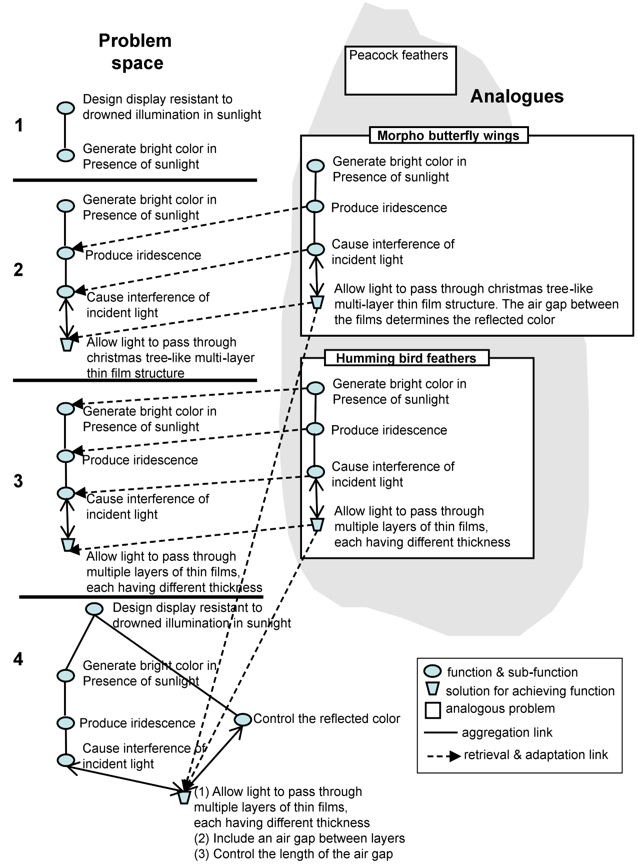

Figure 1: Design of Briteview.

The copepod acted as a source for generating a solution to the first part (slow and stealthy motion) of the now two-part problem. While foraging for food, a copepod is unnoticeable to its prey because it moves its appendages rhythmically in a way such as to minimize the wake produced in water. The knowledge of this mechanism, known as "metachronal beating pattern," was transferred from the copepod source to create a partial solution.

Next, the designers had to address the second sub-function (stealthy fast motion). They used the squid locomotion as an inspiration for achieving this function.

Some squids implement single orifice, interrupted, jet propulsion for forward motion. This mechanism simultaneously addresses two constraints. First, this kind of locomotion is much faster compared to the copepod's locomotion. Second, this kind of locomotion is stealthy because its wake matches the external disturbances that naturally occur in the surrounding water. The stealth achieved here (wake matching) is significantly different from the way stealth is achieved in copepod motion (wake minimizing).

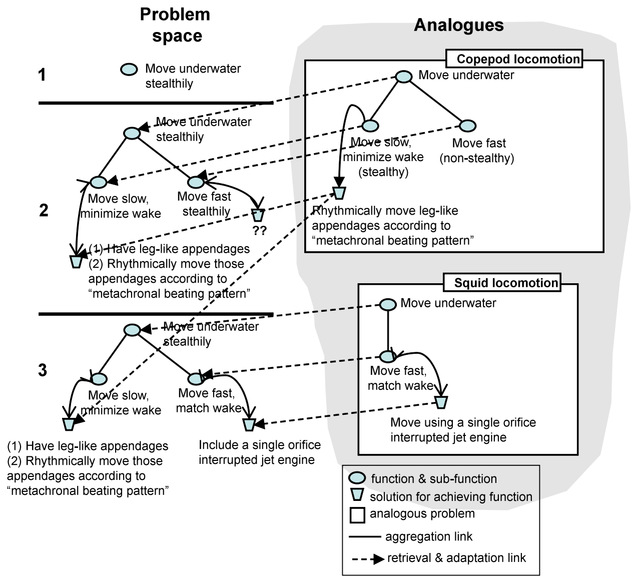

Figure 2: Design of Eye in Sea.

Figure 2 pictorially depicts the generation of this solution. Step 1 depicts the nature of the problem space early in the design. The main function is to move underwater stealthily. In Step 2, the function of moving underwater is decomposed into sub-functions: moving slowly and moving fast, based on the decomposition that exists in the source design of a copepod. The solution to the function of moving slowly by minimizing wake (using "metachronal beating pattern" of legs) is adapted to generate a partial solution as shown in Step 2. But the function of moving fast, yet stealthily remains unresolved in Step 2. In step 3, the analogue of squid is retrieved to address this function. Its solution of using a single orifice, interrupted, jet engine for movement is transferred to the current problem to generate the other partial solution. These two partial solutions are aggregated to achieve the trial design.

InvisiBoard

The goal of this project was to conceptualize a new kind of surfboard that prevented the formation of the surfboard and surfer silhouette (which resemble the silhouette of a shark prey when seen from below) to prevent "hit-and-run" shark attacks due to mistaken identity. This problem was biologized as: "how do organisms camouflage themselves in water to prevent detection by their predators?" The following biological systems were considered as potential sources of inspiration. (i) Indonesian mimic octopuses are expert camouflage artists. They can mimic various animals based on which predator is close by. Upon studying closely, this source was rejected because the surfboard is a rigid body and does not afford the same flexibility as the body of an octopus. (ii) Bullethead parrotfish use the principle of pointillism to camouflage themselves. When viewed at close range, the fish appear bright and colorful but when viewed from a further distance, the combination of the complementary colors creates the illusion that the fish is grey-blue. This trick blends the parrotfish into the backlight of the reef, and in essence it disappears. (iii) Pony fish achieve camouflage by producing and giving off light that is directly proportional to the amount of ambient downwelling light for the purpose of counter-illumination.

Designers chose the pony fish as their source of inspiration. The function of camouflage now indicated the sub-function of producing a glow on the ventral side of the surfboard to match the ambient downwelling light in order to prevent the formation of the silhouette. Now the issue became the mechanism of producing the light that achieved this function. In the case of pony fish, designers understood that the light is produced by bioluminescence – the light-producing organ of the fish houses luminescent bacteria Photobacterium leiognathi. This light is channeled from the light-producing organ to the ventral side and dispersed by creating rectangular light spots on the ventral side. Therefore, the function of producing ventral glow was decomposed in other sub-functions: produce light, channel and disperse light.

In order to produce light for the surfboard, the traditional means of having an onboard light source and a power source was considered an inferior solution. The search for alternate means of producing light sparked another round of search for biological sources of inspiration, which led them to an organism called Brittle star (a kind of a star fish). This organism implements the mechanism of photoreception. The dorsal side of the Brittle star is covered with thousands of tiny eyes, or microscopic lenses, making the entire back of the creature into a compound eye. This mechanism can be used to collect surrounding light rather than having to produce luminescence as in Pony fish. This suggested a design in which the top of the surfboard would be covered with (suitably distributed) tiny lenses to collect the sunlight incident upon the surfboard.

In order to channel and disperse the light collected to the bottom, their design incorporated embedding optic fibers within the surfboard. One end of these cables would be connected to the lenses on the topside and the other end would be positioned on the bottom side. Although this would channel and disperse light, it would lead to spots of brighter and dimmer light when seen from below the surfboard. This would still produce a silhouette, albeit of a different kind compared to the normal surfboard. To counter this, they had to think of another sub-function:

disperse light to mimic the wavy pattern of the ocean surface. In order to achieve this function, their final design included adding a layer of "pattern light diffusers" on the bottom of the surfboard, which disrupts the pattern of light (coming from the optical fibers) in controlled ways. This layer could be structured to mimic the wavy pattern of the ocean surface.

Figure 3 shows the generation of this. Step 1 depicts the nature of the problem space early in the design. The main function is the prevention of silhouette. Step 2 shows the retrieval of the pony fish analogue and the creation of two sub-functions: produce light, and channel and disperse light. For the first sub-function (produce light), Step 2 depicts the following: (i) solution in the source design (bioluminescence) is not transferred, and (ii) the simple solution of mounting a light and power source is rejected. For the second sub-function (channel and disperse light), a fiber optic-based solution is proposed in Step 2.

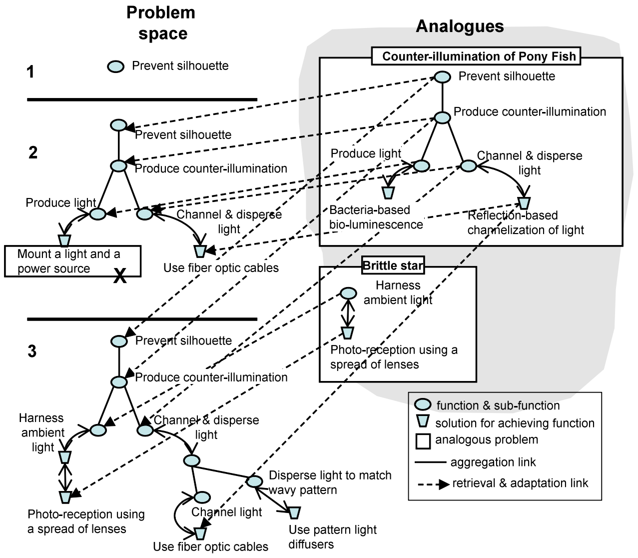

Figure 3: Design of InvisiBoard.

In Step 3, the search for a solution to the function of producing light has been transformed into "harness ambient light." A search based on this transformed function has led to the retrieval of the Brittle star analogue and the transfer of the photoreception solution. Step 3 also depicts how the evaluation of partial solution of Step 2 has indicated that using fiber optic cables alone for both channeling and dispersing light does not eliminate the silhouette (but merely creates a different kind of silhouette). This has led to further decomposition of the original "channel and disperse light" function into two individual sub-functions. The channel light sub-function is still done through fiber-optic cables, but the dispersion is done through specialized "pattern light diffuser" devices. Knowledge about the diffuser devices was based on background domain knowledge and not gained by analogy as far as we can tell.

Discussion

Many aspects of biologically inspired design seem particularly interesting from the perspective of case-based reasoning. Firstly, biologically inspired design is inherently interdisciplinary, necessitating cross-domain (or distant) analogies across two disparate domains (e.g. engineering and biology). To locate cases in different domains that are not indexed *a priori* for the current context of the designer, and to transfer knowledge from those cases, designers seem to employ a number of different strategies (discussed below). Secondly, biologically inspired designing is a very open-ended task. The problem solving occurs over long periods of time and the problem continuously evolves during the design process. (The design projects we studied were one semester long.) Thirdly, there is a lot of learning involved in the process of design. Since the knowledge of biology is unfamiliar to engineers, there is a great deal of exploration of biological literature and learning involved at all stages of the design. Fourthly, case adaptation is very complicated. It often entails run-time composition of partial solutions abstracted from multiple cases. Further, the materials and processes available in nature are very different from the resources available in the engineering domain. Therefore, even if a suitable biological case is found, adapting the design of that system to human domains can prove to be extremely complex. Fifthly, our studies indicate that for about half of design problems, biologically inspired designs tend to be compound analogical designs (Vattam, Helms & Goel 2008): solutions to complex design problems employ multiple cases to solve different design problems that may arise during the design process. In other words, a compound analogical design entails a blending of many design ideas taken from various different source cases. We elaborate on two of these features of biologically inspired design below.

Compound analogical design

Our studies show that the number of compound analogical solutions is significant enough to merit attention. In the Fall 2006 study, six of the nine (66%), and, in Fall 2007 study, four out of ten (40%), biologically inspired designs were based on compound analogies.

Single Source Analogies. Recent research on design, especially creative design, has explored the use of analogies in proposing solutions to design problems in the conceptual phase of the design process. To date, a number of models of analogical design have been proposed (e.g., Goel 1997). Applying any one of these models provides only a partial account of biologically inspired design because they are all single source-based solution generation models. That is, given a target design problem, the design generation process proceeds to retrieve a suitable case and modifies or adapts the design knowledge in the retrieved case to generate a solution to the target problem. Single source-based models can be contrasted with compound analogical models in which the final design solutions are compositions of multiple partial solutions, where each partial solution is based on retrieval and adaptation of a different biological case.

Compilation of problem decomposition. With respect to compound analogical design, Smyth, Keane & Cunningham's (2001 Déjà Vu system seem particularly relevant. In the context of software design, the Déjà Vu case-based system uses *hierarchical case-based reasoning* to generate designs. In hierarchical case-based reasoning, problem decompositions to known problems are already precompiled into cases in the case-base. When a new problem comes, the relevant problem decomposition is first retrieved to obtain the knowledge of the sub-problems. The sub-problems are then used to retrieve the simpler, solved cases from the case-base and the overall solution is composed from the sub-solutions. One difference between the hierarchical case-based reasoning model and compound analogical design in biologically inspired design is that the former only deals with within-domain cases. An even more important difference is that in Déjà Vu, the problem decomposition is already compiled into the cases. But in compound analogical design, the problem decomposition is generated dynamically and incrementally through interaction with cases the problem solver has thus far accessed from memory.

An account of compound analogical design. An examination of the design process used in the projects involving compound analogies showed a complex interplay between the processes of problem decomposition and analogical transfer. Of course, that a design team decomposed a large, complex design problem into smaller, simpler problems is unsurprising. However, a deeper examination of the interplay between problem decomposition and analogical transfer revealed the opportunistic process of compound analogies. Figure 4(a) illustrates one interpretation of the designers' problem solving in generating their design solutions. In the simplest case of compound analogical design, the designer, once presented with a problem, decomposes the problem into sub-problems to create a problem hierarchy. Assuming that the problem is decomposed along functional lines (alternative decompositions are possible) each node in this hierarchy is a function to be achieved. Each function is used as a cue to retrieve known solutions that achieve that function. Solutions are transferred to the current problem, and aggregated to generate the overall solution. Note, in this case, the problem decomposition is known when the problem is presented.

In other cases, where it is not obvious to the designer how to decompose a problem, the designer can search for an analogous solution based on the high-level problem itself. This retrieved analogical source provides both a potential solution and, through a more explicit understanding of the workings of that solution (a solution decomposition), insight into the further decomposition of the problem. This solution decomposition in the source design can be brought into the current problem space as shown in Fig. 4(b). Each new node from the source solution decomposition that is integrated into the problem space can act as an additional c cue for retrieving another set of solution analogues. This process can continue iteratively leading to the incremental development of the problem space. At every stage of this iterative process, the designer can evaluate the partial solutions available and decide to take further actions. The iterative feedback between these two processes accounts for the both incremental evolution of design problems, as well as for our observed compound design solutions.

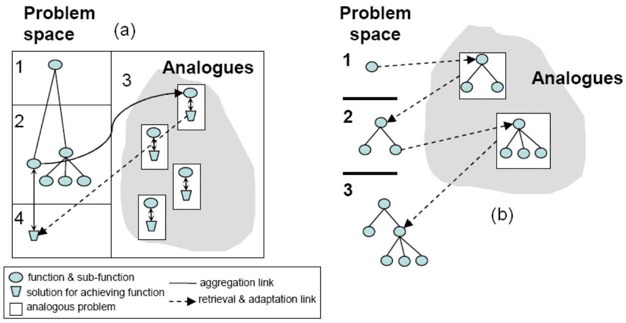

Figure 4: Compound Analogical Design.

Cross-domain retrieval

An important characteristic of the above process is the ubiquity of the retrieval process across the entire problem-solving process. Further, the retrieval process in biologically inspired design is dominated by search for cases originating in a domain different from that of the current problem. Designers employ a number of different strategies to locate cross-domain cases, which are not a priori indexed for the context of the current problem.

Functional indexing and retrieval. In this strategy, past design cases are indexed by the functions they achieve (e.g., Goel & Bhatta 2004). During initial stages of the biologically inspired design, designers employing this strategy focus on functions to be achieved and ignore or reduce structure and material influences. Using functions as cues for retrieval, and by indexing biological cases (e.g., lotus leaf, Gecko's feet, butterfly wings) using interesting functions performed by those systems (e.g., maintain the surface clean, adhere to different surfaces, produce iridescence, respectively) allows designers to categorize the cases in a domain-neutral form and enables access to both within-domain cases and cross-domain cases.

Schema-based retrieval. In this strategy, any features of the problem at hand initially drive the retrieval of a number of cases. Sometimes, one of these cases will be sufficient to address the problem at hand. At other times, the exposure to a wide range of related cases serves to promote the induction of generalized knowledge schemas (e.g., design patterns). Such schemas embody an abstract conceptual understanding of the nature of problems addressed in those precedent cases (Holyak & Thagard 1995). They also serve to enable the recognition of the more general problem 'types' and what is common and different across those problem types. This abstract knowledge, in addition to serving as a framework for organizing cases, also provides additional cues for the subsequent retrieval of other cases, which might otherwise be inaccessible.

Problem transformation aided retrieval. "Biologizing," seen in the three case studies above, is a simple case of this strategy. Here, designers abstract a specific function from the current problem (e.g., stopping a bullet) and transform it into a broadly applicable biological function (e.g. what characteristics do organisms have that enable them to prevent, withstand and heal damage due to impact). The biologized function is then used to retrieve the biological cases. In addition to biologizing from a single initial problem description, such transformations can also occur at the schema level. Designers' exposure to a number of previous cases promotes the induction of abstract schemas.

Deferred goal and recall. In this strategy, reminding works in the opposite direction - from cases to problems (e.g., Will & Kolodner 1994). When an attempt to solve a problem has failed, designers usually leave it aside (the goal is deferred). Later, the designer serendipitously encounters a relevant case, and this new case prompts the recall of that unsolved problem.

Conclusions

As we indicated in the introduction, the usefulness of our meta-analysis of extreme case-based reasoning in biologically inspired design lies in the set of research issues and themes it suggests. Our analysis of biologically inspired design reveals a complex interplay between solution knowledge, analogical references and problem understanding, leading to the incremental, iterative development of compound solutions. In this paper we proposed a high-level process of compound analogical design that tries to capture some of these features. This process account extends the traditional accounts of case-based design by incorporating some of the interactions between two distinct processes, case-based reasoning and problem decomposition. This puts forth a challenging set of research issues and themes for case-based reasoning.

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