Compound Analogical Design: Interaction between Problem Decomposition and Analogical Transfer in Biologically Inspired Design

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Biologically inspired design (BID) can be viewed as an example of analogical design from a cognitive standpoint. Existing models of analogical design cannot fully account for the generation of complex solutions in BID, especially those which contain compound solutions. In this paper we develop a conceptual framework of *compound analogical design* that explains the generation of compound solutions in design through opportunistic interaction of two related processes: analogy and problem decomposition. We also present our study of BID and apply this framework to analyze three sample designs that contained compound solutions.

Introduction

Biologically inspired design (BID) [1], [2] uses analogous biological systems to develop novel solutions for engineering problems. From a cognitive standpoint, BID can be viewed as an instance of analogical design where novel design representations in one domain (engineering) get created by drawing upon existing representations in a different domain (biology). In design literature, a number of models of analogical design have been proposed, all of which employ the generic cognitive process of analogical reasoning (e.g., [3], [4], [5], [6] [7], [8]). Existing models of analogical design explain the generation of solution for a target problem by reminding and transfer of elements from a known design (source design). Here we argue that the explanatory adequacy of existing models has to be enhanced to account for the complexity of some of the design solutions that emerge in BID. Specifically, the traditional accounts of analogical design cannot fully explain the generation of *compound solutions* noted in our study of BID. We define compound solution as one that contains compound analogies – the overall solution is obtained by combining solutions to different parts of the problem where solution to each part is derived from a different (biological) source. We have developed a high-level conceptual framework of *compound analogical design* for understanding the generation of compound solutions in the context of BID and for analyzing the designs that we encounter in our studies. This framework extends the traditional accounts of analogical design by incorporating the interaction between two related processes, *analogy* and *problem decomposition*.

In this paper, we first give an overview of BID and details of our study. In the study presented here, we observed designers engaged in BID in the context of an interdisciplinary introductory course on BID offered at Georgia Tech in the Fall of 2006. Our presentation of this study will mostly focus on sample designs which contain compound solutions. Next we will present our conceptual framework of compound analogical design. Finally, we will analyze three sample designs using our framework and present our conclusions.

Biologically inspired design

Biologically inspired design (BID) is an important recent movement in design that espouses the adaptation of functions and mechanisms in biological sciences to solve human problems. BID is usually associated with engineering (although not necessary) where the target design problems are typical of the problems faced by designers in different engineering disciplines like mechanical and aerospace engineering, electrical and computer engineering, chemical engineering, biomedical engineering, etc. The potential for BID has been documented by Vincent and Mann ([9]) with a number of examples including drag reduction based on dermal riblets on shark skin, deployable structures based on flowers and leaves, tough ceramics based on mollusk shells, underwater glues based on mussel adhesive, self-cleaning paint based on the lotus leaf, etc. “Products” of BID are usually intended to be interesting in some way and are sometimes a radical departure from the past designs.

Instances of successful BID are relatively rare and a need is felt to explicitly promote BID among engineering community [9]. One of the approaches to promoting BID has been through education – train engineers in biology too. The other approach is to form interdisciplinary design teams of engineers and biologists where the complementary skills of both engineers and biologists can be taken advantage of. These approaches are theory-thin approaches and merely hope that success is achieved by putting all the right ingredients together. We adopt a more explicitly theoretical approach. We claim that BID remains mentally challenging despite the continual advancement of training and interdisciplinary techniques. Understanding the cognitive basis of BID helps us understand those aspects of BID that are challenging and can help us better promote BID through methodology and tool development.

The context of our study

Our study was conducted in the in the context of an interdisciplinary introductory course on BID offered at Georgia Tech in the Fall of 2006. This is a project-based learning course in which about 40 students work in small teams of 4-5 students on assigned projects. The projects involve identification of a design problem of interest to the team and conceptualization of a biologically-inspired solution to the identified problem. Each team writes a 15-20 page report and makes an oral presentation near the end of the semester. This course was primarily structured into lectures, found object exercises, journal entries, and a final Design Project.

Lectures: A large percentage of lectures focused on exposing the students to existing BID case-studies. A small percentage of lectures were devoted to the “cognitive practices” involved in BID work (e.g., reframing engineering problems in biological terms, functional decomposition of a problem, adopting design processes, optimization, and the use of analogy in design). Some lectures posed problems for the students to solve in small group as within-class exercises.

Found object exercises: These exercises required students to bring in biological samples and analyze the “natural” solutions employed by these samples. The intention was to expand the awareness of biological solutions, provide hands on experience with biological systems, and encourage the students to dig progressively deeper into the functions of biological systems. Students formed small groups during these in-class exercises, with each group discussing the merits of their found objects’ solutions.

Journal entries: Students were required to write about their classroom experiences and document their own design thinking in a journal that each student maintained.

Final design project: Term projects grouped an interdisciplinary team of 4-5 students together based on interest in similar problems or solutions.

Each team typically had one student from biology and a few from different engineering disciplines. After each student submitted two problems of personal interest, the instructors created groups based on (1) similarity of interests, and (2) balance of disciplines. This grouping provided each team with a constrained space of problems to explore. Each team was responsible for identifying a problem, exploring a number of solution alternatives, and developing a final design based on one or more biological solutions. Towards the end of the course, teams presented their final designs.

As observers, we attended all the classroom sessions, collected all course materials, documented lecture content, and observed teacher-student and student-student interactions in the classroom. We also did *in situ* observations of a few of the student teams engaged in their design projects. Our observations paid special attention to (i) classroom instruction and dialogue, (ii) student group discussions in the classroom, (iii) student and instructor examples and exercises, (iv) student group discussions outside the classroom, and (v) student interim and final presentations. We minimized our intervention, only occasionally asking clarifying questions.

Our observations focused on the cognitive practices and products of the designers. In terms of the practices, we observed and documented the frequently occurring problem-solving and representational activities of designers as part of the design process. Some of these activities were part of the standard design process taught by the instructors. Others emerged during practice. In terms of the design products, we observed and documented the “design trajectory” – the evolution of the conceptual design over time.

Although this study was conducted in the context of a classroom setting, we approached the study from the design cognition perspective as opposed to the learning sciences perspective. That is, we were less concerned about the pedagogical approach and the learning outcomes of the course itself. Although we believe that our research will have long term implications on the design and the conduct of this course, we were not directly involved in the decision-making regarding the design of this course. From our perspective the classroom merely provided a setting where we could observe designers engaged in BID.

Most instructors and lecturers were not design experts per se, but had many years of practical biologically inspired design experience and focused classroom lectures on sharing their biologically inspired design experience through specific case studies. Most students, although new to biologically inspired design, had previous design experience. Out of the 45 students, at least 32 had taken a course in design and/or participated in design projects as part of their undergraduate education. Throughout this paper, we will refer to the students in the class as designers.

Study Findings

Here we provide a short summary of our findings relevant to the subject matter of this paper. Additional details of this study are documented in our technical report ([10]). First, we noted the existence of two high-level processes for biologically inspired design based on two different starting points – *problem-driven* and *solution-driven* process. In a problem-driven approach, designers identified a problem which formed the starting point for subsequent problem-solving. They usually formulated their problem in functional terms (e.g., stopping a bullet). In order to find biological sources for inspiration, designers "biologized" the given problem, i.e., they abstracted and reframed the function in more broadly applicable biological terms (e.g., what characteristics do organisms have that enable them to prevent, withstand and heal damage due to impact?). They used a number of strategies for finding biological sources relevant to the design problem at hand based on the biologized question. They then researched the biological sources in greater detail. Important principles and mechanisms that are applicable to the target problem were extracted to a solution-neutral abstraction, and then applied to arrive at a trial design solution. In the solution-driven approach, designers began with a biological source of interest. They understood (or researched) this source to a sufficient depth to support extraction of deep principles from the source. This was followed by finding human problems to which the principle could be applied. Finally they applied the principle to find a design solution to the identified problem.

Interesting trends were noted in the above processes. First, we noted how the problem-driven process was "given" to the designers by the experts as a normative methodology for BID, while the solution-driven process emerged in practice. Second, we noted that once a biological solution is selected, that solution constrained the rest of the design process in many ways. For instance, when the process was solution-driven, the initial source fundamentally drove the design process, from problem definition through final design. On the other hand, in the problem-driven process, a particular biological solution became a source of design fixation, limiting the range of possible designs. Third, throughout the process designers consistently fell prey to a common set of mistakes (judged by experts/instructors) like vaguely defining problems, over-simplification of complex functions, using "off-the-shelf" biological solutions, misapplied analogy, improper analogical transfer, etc. Finally, we noted that a substantial number of design solutions generated were compound solutions (about 66%), which are the focus of this paper.

Sample biologically inspired design projects

Table 1 provides samples of design problems and solutions that we documented in our study. Details about each project are available in [10].

Table 1 Sample BID projects from our study

Project	**Design**	**Type**	**Inspiration**
Abalone armor	A self-healing bullet-proof vest that combines the qualities of strength and toughness	non-compound	Material of abalone shell (nacre)
Traffic control	A traffic system that reduces congestion on urban roads	non-compound	Traffic load-balancing in ant colonies
Shell phone	Cell phone case that is tough and resistant to everyday wear and tear	non-compound	Material of abalone shell (nacre)
BioFilter	Portable, stand-alone, home air filtration system	compound	Adhesive properties of spider silk + porous properties of diatoms
Brite-View	Electronic display that is resistant to drowned illumination in bright sunlight	compound	Hummingbird feathers + Morpho butterfly wings
Eye in the sea	Underwater micro-bot with stealthy motion	compound	Copepod locomotion + squid locomotion
Invisi-Board	Surfboard that does not produce silhouette when seen from underwater to prevent shark attacks	compound	Counter-illumination mechanism in pony fish + photo-capture mechanism in Brittle star
iFabric	A thermally responsive and adaptive fabric for clothing that provides thermoregulation for the wearer	compound	Bee hive material + blood circulation system of arctic wolves
Robo-Hawk	Aerial bomb detection device	compound	Chemical sensing in dogs + scent tracking movement of sea gulls

Six of the above nine projects yielded compound solutions. These solutions are of interest to us in this paper. Out of those six, we choose three projects (highlighted in Table1) for our analysis presented in later sections.

Compound Analogical Design: A conceptual framework

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. Analogical design involves reminding and transfer of elements of solution for one design problem to the solution for another design problem, where the selected design elements may be components, or relations between components, or configurations of components and relations [11]. To date, a number of models of analogical design have been proposed. An important distinguishing feature among them has been the domain of application. Different researchers in different design domains have arrived at their own accounts of how analogical design happens in their respective domains. For instance, [8] and [5] provide examples of analogical design in architecture; [11], and [3] provide an account of analogical design in electro-mechanical device design; [12] provides an account analogical design in the domain of software design; etc.

Another crucial distinguishing feature among the existing models has been the capability to handle cross-domain analogies. A majority of existing models are examples of with-in domain analogical design. That is, if the problem is to design an electronic display screen, for instance, they can explain how a solution to this problem can be generated by retrieving and adapting existing (or previously encountered) designs of electronic displays. They cannot, however, explain how the knowledge about the structure of butterfly wings can be retrieved and adapted to generate a new design for an electronic display. One fundamental requirement for a model that is applicable to BID is this capability to carryout cross-domain analogical retrieval and transfer. Some models of analogical design do address the issue of cross-domain retrieval and transfer of knowledge. In [3], for example, when a new design problem is encountered, the function to be achieved in the new design (or some abstraction or transformation of that function) is used as a cue to retrieve an analogous design, which can originate in another domain. The retrieved design is then modified or adapted to generate a solution to the target problem.

Although some of the existing models are capable of handling cross-domain analogies, they cannot account for the following aspects of design problem-solving documented in our study. First, the existing models only model problem-driven generation of solution. They do not adequately explain how, starting with some existing design solution, a relevant problem can be found to which this solution is applicable. Rather than starting with a problem and searching for solutions, in a solution-driven approach one starts with a solution and searches for problems in the human domain.

Second, more importantly, most existing models of analogical design are *single source-based* solution generation models. That is, given a target design problem, the process proceeds to retrieve a suitable analogue (within-domain or cross-domain) and modifies or adapts the retrieved design to generate a solution to the target problem. From the cases of BID presented here, it is apparent that this form of one-shot analogical design from a single source is not adequate for generating complex designs. In complex design tasks, multiple sources are often needed to solve different parts of a complex problem. This immediately suggests interplay between two related processes, analogy and problem decomposition.

Interplay between Analogy and Problem Decomposition

Solving complex problems by decomposition is a common strategy. There are just as many models of design problem-solving based on decomposition as there are based on analogy. The strategy of decomposition, where designers break large, complex problems into small, less complex, manageable one is not new. But when we make the decompositions explicit in the context of analogical design, it becomes apparent how the processes of decomposition and analogy influence each other. We will characterize their interplay here, leading to the development of our high-level conceptual framework of *compound analogical design*. We will use this framework to analyze our sample bio-inspired designs in the next section.

In the simplest case of compound analogical design, when a target design problem is presented, designer iteratively decomposes the problem into sub-problems to get a problem abstraction hierarchy (based on his/her background domain knowledge). Assuming that the problem is decomposed along functional lines, each node in this hierarchy is a function to be achieved. Each function (node) can be used as cue to retrieve known designs that achieve that function. Solutions from known designs are transferred to the current problem. Solutions to different functions are aggregated to generate the overall solution. Complications can arise during the reintegration of solution parts if the problem cannot be cleanly decomposed into independent sub-problems. Complications can also arise due to constraint propagation. Figure 1(a) shows this simple case of compound analogical design. An example of this case can be found in the RoboHawk project (see Table 1) where the problem of designing an aerial bomb detection device immediately suggested two sub-functions: sensing certain chemicals, and navigating towards the chemical source. These sub-functions, however, were not independent of each other (the method of sensing affected the method of navigating and vice versa). This decomposition was based on designers' background knowledge.

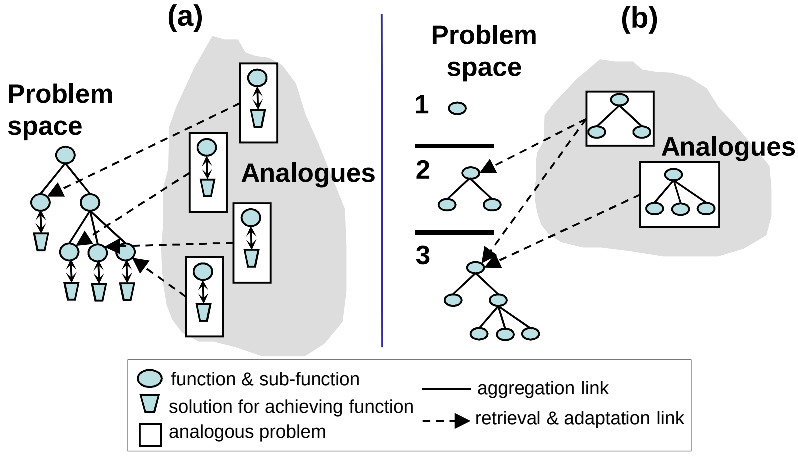

Fig. 1 (a) a simple case, and (b) a more realistic case of compound solution generation in design

In many cases, it may not be obvious to the designer how to decompose a problem into manageable subparts or the designer may not be happy with a known decomposition. The designer might then search for an analogous design based on the high-level problem itself. Finding one will allow the designer to adapt the known design to solve the current problem. This retrieved source design will not only provide a potential solution, but a deeper understanding of it will allow the user to infer the problem decomposition in the source design. This decomposition in the source design (along with solutions to the sub-problems) can be "brought into" the current design space as shown in Figure 1(b).

Each new node from the source design decomposition can further act as cues for retrieving another set of design analogues. This process can continue iteratively leading to the incremental development of the solution. At every stage of this iterative process, the designer can evaluate the partial solution generated and can decide to take further actions (decompose based on background knowledge, or analogize and find solution, or analogize and grow the problem decomposition, etc.). This is a more flexible case of compound analogical design where the process of problem decomposition and analogical reasoning interact opportunistically, dynamically and in a more context-dependent fashion, accounting for the incremental nature of the evolution of complex design solutions. Examples of this complex case of compound analogical design follow in the next section.

Analysis of three designs using the conceptual framework of Compound analogical design

Project 1: 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. The 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 2 shows the generation of this solution using the framework of the compound analogical design. Step 1 depicts the problem space early in the design. The overall function "design a display" has been decomposed based on the background knowledge 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 Morpho butterfly wing design) into the trial design generated in Step 3.

Project 2: Eye in the Sea

The goal of this project was to design an underwater micro-bot with locomotion modality that would ensure stealth. The problem was "biologized" 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 and squid.

The initial research for the underwater micro-bot 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-like appendage movement) for achieving motion underwater. A slow and stealthy rhythm was used during foraging for food, and a quick but non-stealthy rhythm was used during escaping from predators. This understanding led the designers to decompose their original problem into two separate functions, one for slow and stealthy movement, and one for rapid, yet stealthy movement.

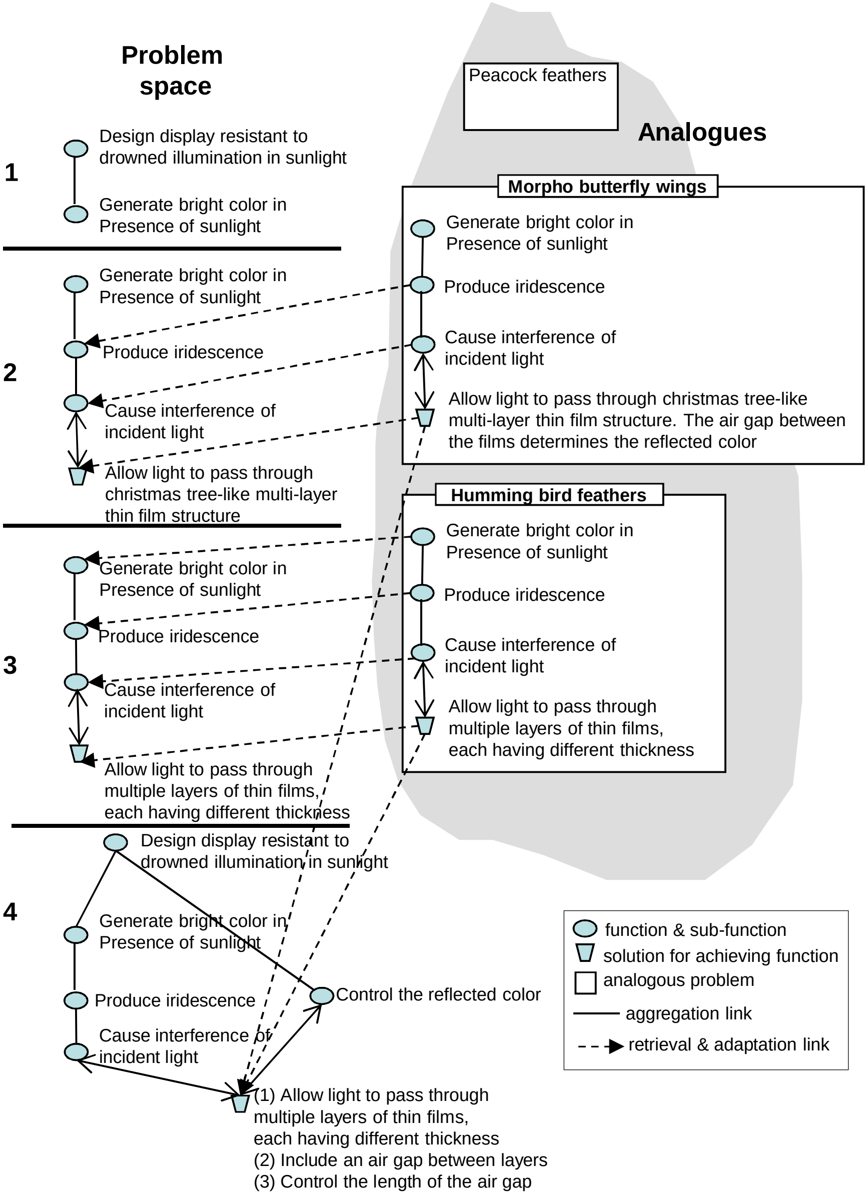

Fig. 2 Design trajectory of the BriteView project

Copepod acted as a source for generating a solution to the former part of the problem (slow and stealthy motion). While foraging for food, a copepod is not noticeable 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 a 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 3 develops a model of the generation of this solution using the framework of the compound analogical design.

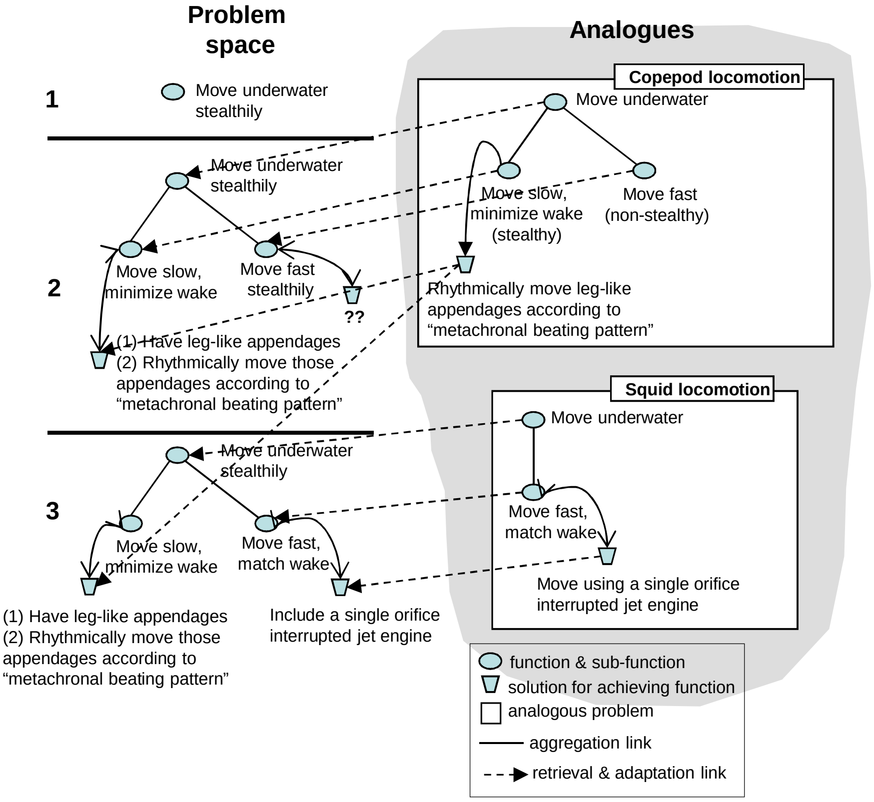

Fig. 3 Design trajectory of the Eye in the Sea project

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.

Project 3: 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 parrot fish uses 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 achieves 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 photo-reception. 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 top side 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 4 shows the generation of this solution using the framework of the compound analogical design. 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 (bio-luminescence) 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.

In Step 3, the search for a solution to the function of producing light has been transformed into “harness ambient light.” We do not have a good explanation of this function transformation. A search based on this transformed function has led to the retrieval of the Brittle star analogue and the transfer of the photo-reception 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.

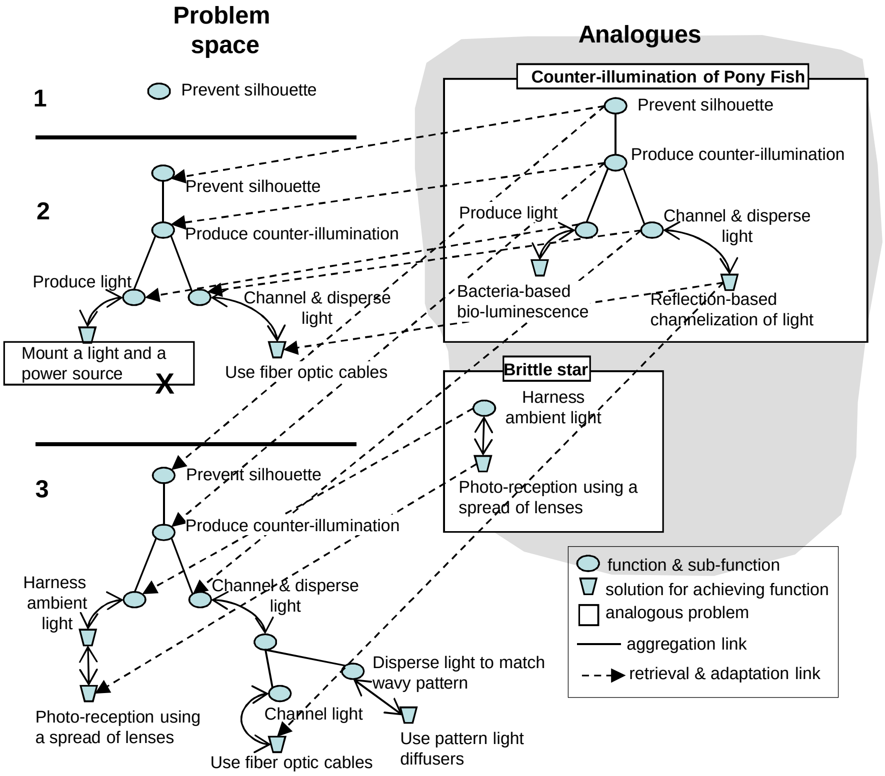

Fig. 4 Design trajectory of the InvisiBoard project

Related research

There are few cognitive accounts of biologically inspired design available in the literature. The available studies focus mostly on the effect of external representations on the number and quality of generated designs. For example, Linsey *et al.* ([13]) found that when compared with using only diagrammatic representations of biological systems, combining diagrams with functional descriptions increases the chances of successful analogies. In contrast, our work provides a more descriptive account of biologically inspired design, with a focus in the use of compound analogies.

In a different context, viz., software design, Smyth *et al.* ([12]) have described Déjà Vu, a system that uses hierarchical case-based reasoning for generating design solutions. Their model of design does combine problem decomposition and analogy (specifically, case-based reasoning). One important difference between our work and theirs is that, unlike case-based reasoning, biologically-inspired design uses cross-domain analogies. An even more important difference is that while in Déjà Vu, the problem decomposition is already compiled into the cases. But in our model, the problem decomposition is generated dynamically and incrementally, and is interleaved with the process of analogy.

Recently there have been a few attempts to build computational tools for supporting biologically inspired design. The Biomimicry Institute provides an online library of research articles on biological systems. Chakrabarti *et al.*'s ([14]) Sapphire tool represents the structure, behaviors and functions of biological and engineering systems in a uniform representational scheme. It retrieves biological and engineering designs based on matches between functional abstractions of the systems and functional abstractions used in a problem description. Chiu and Shu ([15]) use latent semantic indexing to find a match between functional abstractions. Insofar as we know, none of these efforts addresses the issue of compound analogies in biologically inspired design.

Conclusion

Our overall goal is to understand the cognitive basis of BID and propose design methodologies and tools based on this understanding. To come to such an understanding we first conducted a study of designers engaged in BID and identified some of the salient aspects of BID [10]. A closer look at the design products and processes in BID revealed a complex interplay between knowledge of biological systems and knowledge of engineering problems, leading to the incremental, iterative development of compound solutions. In this paper, having noted that existing models of analogical design cannot account for the generation of compound solutions, we have developed a high-level conceptual framework of *compound analogical design* to address this gap. This framework extends the traditional accounts of analogical design by incorporating the interaction between two related processes, analogy and problem decomposition. We have applied this framework to analyze three sample designs from our study that contained compound solutions.

We draw two main conclusions from our analysis. First, successful BID requires that designers carry rich representations of the systems (both biological and engineered) they bring to bear during design. Further, these rich representations are organized at different levels of abstraction and aggregation that facilitate the decomposition of the target problem and allow retrieval of biological (and engineering) analogues with cues taken from each level. Second, knowledge about functions and mechanisms that achieve those functions are likely to be explicitly captured at each level. Once a mapping is established between an engineering function and a biological function, it leads to the transfer of the associated biological mechanism to the engineering domain, along with any inferences about the functional decomposition in the biological solution. This opportunistic interplay between the decomposition and the analogy-making process is the key to achieving successful compound solution in the context of BID.

Our framework has primarily concentrated on the issues related to the interaction between the analogy-making and problem decomposition processes in the service of generating compound solutions. There is no principled reason to limit the framework to just these processes. Design, especially complex creative design such as BID, involves a variety of other processes such as interpretation and elaboration of the design problem, evaluation and refinement of candidate solutions, reinterpretation and reformulation of the problem, problem abstraction, etc. Our framework can only gain in richness as we go forward by accounting for some of these. In future we also intend to develop a computational model of compound analogical design based on the conceptual framework presented here.

One of the conundrums in research on creativity is that any solution to any problem has to start from what one already knows: so, how is it possible to create novel solutions? For example, if a solution to a new design problem starts from a known design solution to a similar problem, then it is not clear in what sense the design solution to the new problem can be called novel, or the design process called creative. One way of getting around this conundrum is to study design situations in which the solution to the new design problem is a composition of known design solutions to multiple problems. In such a situation, it becomes possible to argue that the design is novel, with the creativity lying in the process of composition. Our conceptual framework of compound analogical design which embodies this intuition will, we hope, encourage discussion into this conundrum of creativity.

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