Prabir Sarkar

S. Phaneendra

Amaresh Chakrabarti[1]
e-mail: ac123@cpdm.iisc.ernet.in

Innovation, Design Study and Sustainability
Laboratory (IDeaS Lab),
Centre for Product Design and Manufacturing,
Indian Institute of Science,
Bangalore 560012, Karnataka, India

Developing Engineering Products Using Inspiration From Nature

Nature can be a major source of inspiration for engineering designers. Biomimicry is often used in specific cases to develop solutions that mimic natural systems. However, knowledge of natural systems is still not used systematically and commonly for inspiring innovative product development, from ideation of solutions to their implementation as products. In ideation, potential solutions to a design problem are generated. To support ideation, two databases are developed with entries having information about natural and artificial systems. A novel generic causal model is developed for structuring information of how these systems achieve their behavior. Three algorithms are developed for analogical search of entries that could inspire ideation of solutions to a given problem. In realization, evaluation and modification of these solutions are carried out by experimenting with these in virtual and physical forms and environments.

[DOI: 10.1115/1.2956995]

1 Introduction

Designs found in nature are wonderful. Nature, through billions of years of trial and error, has produced effective solutions to innumerable complex real-world problems [1], whose functions are often similar to that demanded in engineering products, e.g., heart functioning like a pump [2] or joints with movement as in a mechanism [3]. For both natural and engineering tasks, resources are limited and must be utilized optimally to accomplish the task in a reliable and functional manner. Thus, designs in nature could act as inspirations for the engineering designer [4]. The question is, how to use systematically, the knowledge of these systems to solve design problems?

Vincent [1,5] estimates that "at present there is only a 10% overlap between biology and technology in terms of the mechanisms used" so there is a great deal of potential in this area. Engineers, scientists, and businesses are increasingly turning toward nature for design inspiration. The field of biomimetics, the application of methods and systems found in nature to engineering and technology, has spawned a number of innovations far superior to what the human mind alone could have devised, such as a solar cell inspired by a leaf [6]. Its focus has primarily been on long-term development of specific technologies such as synthetic spider silk [7]. However, there is no general systematic support available for engineering designers to use nature as inspiration for solving design problems—right from *ideation* to *realization* of ideas.

We developed a two-step approach to address this issue. The first step is "ideation," where potential solutions to a problem are generated. The second step is "realization," where these are evaluated and modified by experimenting with them in both virtual and physical forms.

2 Ideation

Inspiration is useful for exploration and discovery of new solution spaces [8]. Evidence of this, for instance, are that the presence of a stimulus can lead to generation of more ideas during problem solving [9], that stimulus-rich creativity techniques positively affect creativity [10], or that individuals stimulated with association lists demonstrate more creative productivity than those without stimuli [11].

Analogy has long been regarded as a powerful means for inspiring novel idea generation, as seen in several systems based on analogy [12,13] and creativity methods developed with the specific aim of fostering analogical reasoning [14], and in other research that have contributed to the understanding and application of analogy [15–18].

Generating a large number of ideas with a variety of principles [19] increases the chances of developing better products [9]; experimenting with ideas in realistic environments makes them more practically viable. Creative products are initiated through inspiration [3,12], where use of analogy is beneficial [1,14,20].

Shu et al. [21] and Shu [22] shown the application of a biomimetic search method to develop ideas on how to center objects in microassembly and remanufacturing [23,20]. Structural analogy has been used to achieve this. Vakili and Shu [23] worked on biomimetics where analogous keywords of a system's function are used to help designers. Single text with synonyms has been used for searching analogous functions. Later Hacco and Shu [20] used Wordnet® and text tags to help find similar words and part of speech in a sentence, similar to natural language processing. Based on the structure of the system, solutions are generated related to remanufacturing.

In our work we have used a combination of words for searching entries and this search can be carried out with single or a combination of SAPPhIRE constructs (see Sec. 2.3). At a broad level of abstraction, our work is similar to Hacco and Shu [20], as we both use synonyms to find alternative solutions. However, we argue that the approach presented here is far more extensive in three ways. First is, unlike Vakili and Shu [23], where only functional analogy has been used, we use functional, behavioral, and structural analogies, using seven layers of constructs from the SAPPhIRE model of causality to carry out the search. The second is combination of analogies from multiple layers can be used in our case to carry out search (see Sec. 2.4). Finally, results of search using multiple analogies can be used in the analogical reasoning itself (see Sec. 2.4).

2.1 Methodology. Earlier, we developed a computational tool called IDEA-INSPIRE that provides analogical ideas of natural or artificial systems as inspirations to designers to support generation of novel solutions for product design problems [4]. The current application focus is novel mechanisms. Our intention is to use the diverse motions that nature exhibits as a source of inspiration for solving product design problems, especially in inspiring creativity and innovation of novel products. The work is not about mimicking natural phenomena but rather getting inspired from primarily the behavioral aspects of these phenomena.

---

[1] Corresponding author.

Contributed by the Computer-Aided Product Development (CAPD) Committee of ASME for publication in the JOURNAL OF COMPUTING AND INFORMATION SCIENCE IN ENGINEERING. Manuscript received September 27, 2006; final manuscript received June 2, 2008; published online August 5, 2008. Assoc. Editor: R. Crawford.

To develop IDEA-INSPIRE, first two databases were developed: one for natural systems (e.g., insects, plants, etc.) exhibiting diverse movements and the other for artificial systems (e.g., vacuum cleaners, clutches, etc.). These systems were then analyzed, and a generic SAPPhIRE model of causality for describing their behaviors was developed. This model has a set of constructs that are used to explain the functioning of an artificial or natural system. Finally, IDEA-INSPIRE software was developed with appropriate interface and analogical search procedures to aid the following. Designers, with a problem to solve, would explore the behavior of the natural or artificial system entries in the databases, and use the constructs of the SAPPhIRE model to describe the problem in terms of the constructs of the language; the software would then search the databases for entries that could be presented to the designers as inspirations to aid ideation to solve the problem. IDEA-INSPIRE is based on the following philosophy: given a design problem, if the designer is exposed to a variety of natural and engineered systems that have similar function, behavior, or structure, ideation should be enhanced.

2.2 SAPPhIRE Model of Causality. The main challenge in developing the model of causality was that it must allow the function, behavior, and structure of a system to be linked to one another in a way common for both natural and artificial systems, and allow describing these at various levels of abstraction. At the center of this work is the development of a uniform functional/behavioral representation for these systems.

We view function as the intended effect of a system [24] and behavior as the link between function and structure defined at given levels; therefore, that is the behavior specific to the levels at which the function and structure of a system are defined. We argue that structure—in a richer representation of causality—must have the flexibility of being represented using multiple views. Such a richer encompassing causal description of the functioning of a system has been developed and described below [4].

The constructs used in the SAPPhIRE model of causality are as follows.

Parts. Physical components and interfaces constituting the system and its environment of interaction.

State. Attributes and their values that define the properties of a given system at a given period of time during its operation.

Physical effect. The laws of nature governing change.

Organ. The structural context necessary for a physical effect to be activated.

Input. The energy, information, or material requirements for a physical effect to be activated.

Physical phenomenon. Potential changes associated with a given physical effect for a given organ and inputs;

Action. Abstract description/interpretation of a state change, a changed state, or an input.

The relationships between these constructs are as follows: *parts* are necessary for *creating organs*. Organs and *inputs* are necessary for *activation* of *physical effects*. Activation of physical effects is necessary for *creating physical phenomena*, which *activates* and *changes* of *state*. Change of state is *interpreted* as *actions* or inputs, and *create or activate* parts. Essentially, there are three relationships: activation, creation, and interpretation [4,25].

The model is acronymed as the SAPPhIRE model, where SAPPhIRE stands for state-action-part-phenomenon-input-organ effect (see Fig. 1).

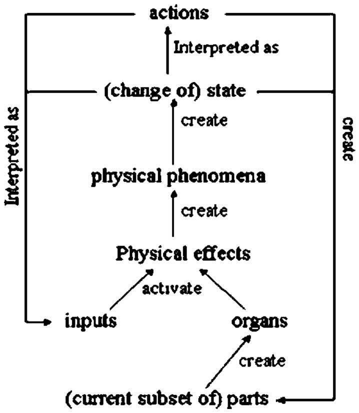


Fig. 1 The SAPPhIRE model of causality

2.3 Representation. Each entry (e.g., in the Appendix) in the databases of IDEA-INSPIRE [4] is described using entry-specific details that are structured using its function, structure, and behavior, as well as using a linked set of SAPPhIRE constructs, videos and images [4]. The databases [4] have over 700 entries. IDEA-INSPIRE is implemented using Microsoft™ VISUAL C++.

Each entry in the databases is described, using the SAPPhIRE constructs (see Appendix), in two forms.

1. A computer understandable form—these are text files containing a set of words used to describe the entry and formatted in a particular way that can be read by the program easily and can be used for efficient search.
2. A human understandable form—these are text files containing paragraphs, explaining the motion behavior of the entry in sentence form.

In the computer understandable form, the content of each entry is divided into a list of actions, state, physical phenomena, inputs, physical effects, organs, and parts; links between various subsets of these together constitute the entry.

In the human understandable form of the entries, these links are expanded in paragraphs (see Appendix for an example).

2.4 Search Strategies. The goal of the search strategies is to support analogical reasoning at multiple levels of abstraction. Using these strategies, a designer should be able to simply browse the entries for random stimulation or systematically search through them with specific purposes. For searching for solutions a designer can use one or many constructs (action, physical effect, etc.) of the SAPPhIRE model, or any combinations of them as input to the software. Presently the software can take three demands and three wishes. Each demand or wish can be depicted by any of the seven constructs. Each of these constructs has a particular way of expressing—verb, noun, and adjective or phrases. A designer can use many combinations of these constructs in order to completely define the problem.

Three search algorithms are developed: simple, combination, and complex searches.

Simple and combination search. While searching for analogical entries, a designer can give one (simple search), or a combination of (combination search) constructs (action, physical principle, etc.) to the software as inputs (see Appendix for an example of an entry).

Complex search. Since each entry is a linked network of SAPPhIRE constructs, analogical solutions could be reached if IDEA-INSPIRE could be searched for, say, entries that share the same principles in the entries that fulfill a given required action or entries that have analogical parts to those having the required action.

2.5 Working Principle. The description of characteristics or constraints obeyed by entries looked for is provided by the designer in terms of verbs, nouns, and adjectives. In order to implement the "translation" of this input into analogical descriptions, clusters of equivalent words (synonyms) have been developed. Clustering of words is carried out beforehand for nouns, verbs, and adjectives and stored in a database for use during translation.

When a designer gives the required input to the software by formulating the problem in terms of a combination of constructs, the software tries to find the best match of the entries in the

Table 1 Efficacy of IDEA-INSPIRE software (D1–D3: designers involved)

	Without using IDEA-INSPIRE			With using IDEA-INSPIRE					
	No. of ideas generated (G1)	No. of ideas selected (S1)	Ratio of S1/G1	No. of ideas generated (G2)	No. of ideas selected (S2)	Ratio of S2/G2	No. of entries explored (E)	Ratio of G2/E	Ratio of G1/G1
D1	9	4	44%	17	6	35%	60	28%	188% (17/9)
D2	6	4	66%	5	3	60%	40	12%	083% (5/6)
D3	8	3	37%	18	6	33%	60	30%	225% (18/8)
Avg.	7.6	3.6	49%	13.3	5	42%	53	23%	165%

descending order of importance, annotating each entry with a weightage as described in Sec. 2.4, which shows how close the entry is to the search input provided.

Since each entry is a linked network of actions, state changes, organs, inputs, effects, phenomena, and parts, analogical solutions can be reached if it is possible to search for, say, entries that share the same principles in the entries that fulfill the required actions or entries that have analogical parts to those that have the required intended action. For search of these kinds, one should be able to construct complex search queries with multiple, intermediate, and final search points of specified types and with specified input types and values. This can be achieved by a multiple search with the following form.

For a given input type, find all outputs of a given type for all intermediate outputs of given types. For instance, one such query is for a given action (input), find all entries (output) that provide actions (intermediate output type) that use the same effects (intermediate output type) as are used by the entries that provide the input action.

Given action→effects used→actions→entries. Such complex search problems should help "discover" solutions that are more difficult to immediately associate with a given design problem (e.g., the input action) and yet are analogically relevant as potential ideas for solving the problem.

2.6 Evaluation of the Ideation Support. Ideation effectiveness of the support was evaluated in *two* stages. In the first stage, three designers were asked to individually generate as *many* ideas as possible to solve design problems without any aid. They were then asked to generate further ideas taking inspiration from entries in IDEA-INSPIRE.

These designers were provided with an instruction sheet that described the problem to be solved and were requested to sketch and annotate the ideas generated by them, identifying the major components for each idea and explaining its working principle. Each designer was provided with a set of numbered blank sheets and was requested to sketch each idea on a different sheet. First, each solved all three problems without aid. Next, each evaluated their ideas, and selected some of them as acceptable solutions.

IDEA-INSPIRE software was then introduced to each designer by the researcher. For each designer and problem, a number of search strings were formulated using input from the designer involved, and IDEA-INSPIRE was used for search of entries to inspire ideation for each problem. The entries were seen by the designer one after another, and if the designer get inspired, (s)he created an idea immediately based on the entry seen. This continued for several search sessions for each problem until the designer expressed termination of this process. There was no time constraint prespecified for any session. After the ideation sessions for a given problem for each designer, the resulting ideas created by the designer were evaluated by the designer, and acceptable solutions among these were selected. Since each idea was presented on a separate numbered sheet, counting the number of ideas did not pose a problem. In any case, the ideas were counted by two individual researchers for accuracy. Each individual ideation session took about an hour, and evaluation/selection about half an hour, taking about 3 h altogether for each designer per problem solving, including ideation unaided, evaluation and selection of these ideas, ideation aided by IDEA-INSPIRE, followed by evaluation and selec-

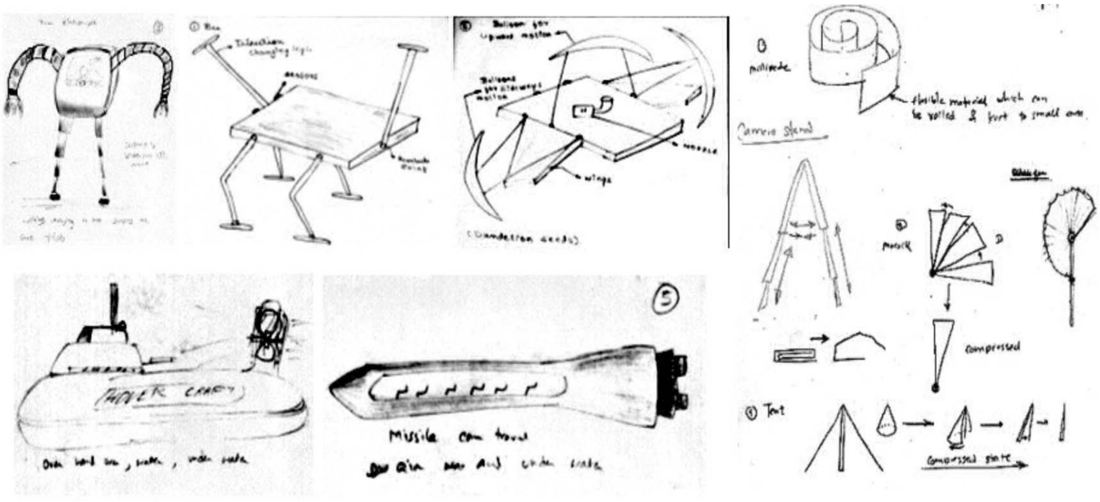
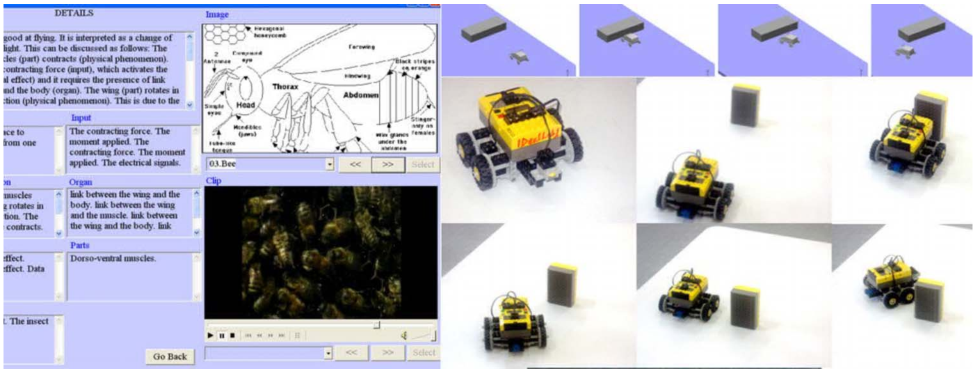


Fig. 2 Some of the initial concepts that the designers generated while solving Problems 1 (left) 2 (right)



good at flying. It is interpreted as a change of
light. This can be discussed as follows: The
cles (part) contracts (physical phenomenon).
contracting force (input), which activates the
l effect) and it requires the presence of link
nd the body (organ). The wing (part) rotates in
tion (physical phenomenon). This is due to the

ce to
from one

The contracting force. The moment applied. The contracting force. The moment applied. The electrical signals.

muscles
g rotates in
tion. The
contracts.

link between the wing and the body. link between the wing and the muscle. link between the wing and the body. link

ffect.
ffect. Data

Dorso-ventral muscles.

. The insect

Fig. 3 An entry of a bee as the source of inspiration (left). Simulation of the intended vehicle moving forward, colliding with the obstacle, retracting after collision, and taking a left turn to avoid the obstacle (top right). Physical modeling of how it avoids an obstacle (bottom right).

tion of these ideas.

On average, each designer was able to generate 165% additional ideas using inspiration from IDEA-INSPIRE than on their own (see Table 1), which indicated the *ideation effectiveness* of the approach. This was assessed using two parameters: one is the enhanced *fluency* of the designers, as seen from the additional ideas generated by them. This is a standard measure used by many creativity researchers in assessing likely *novelty* of the outcomes, such as in Refs. [26–28]. The second is the percentage of ideas selected by the designers themselves as worth developing (about 42%), which indicates the likely *usefulness* of the ideas generated [28,29]. As described by the majority of creativity researchers [26–29], and summarized in our earlier work on developing a common definition of creativity [30], novelty and usefulness are the two basic components of the creative quality of ideas. Therefore assessing ideation effectiveness using these parameters implies the impact of the software in enhancing the creative quality of ideas. This, we argue, happens due to exploration of a larger number of entries by the designers, which get them triggered with newer ideas with varied characteristics, helping them generate greater variety.

In the second stage of evaluation, 12 design students who were in their final stage of their course were offered support of ideation using IDEA-INSPIRE in their respective design problems that they had to solve as a mandatory requirement for their course. The designers participating in these evaluation stages have an undergraduate degree in engineering, up to a year of professional experience in design in industry, and are in the final year of a two year Masters in Design course at the time of the evaluations. Feedback from this second informal evaluation (based on their exit comments on the usefulness and usability of the software for their purpose) indicated both an enhancement of the number of new ideas generated (as in the first evaluation) and ease of use of the software.

This, however, does not support attainment of realizability of these ideas—an essential aspect of engineering product development. For this, a realization support was developed and used in another study, where working prototypes to embody these ideas were created.

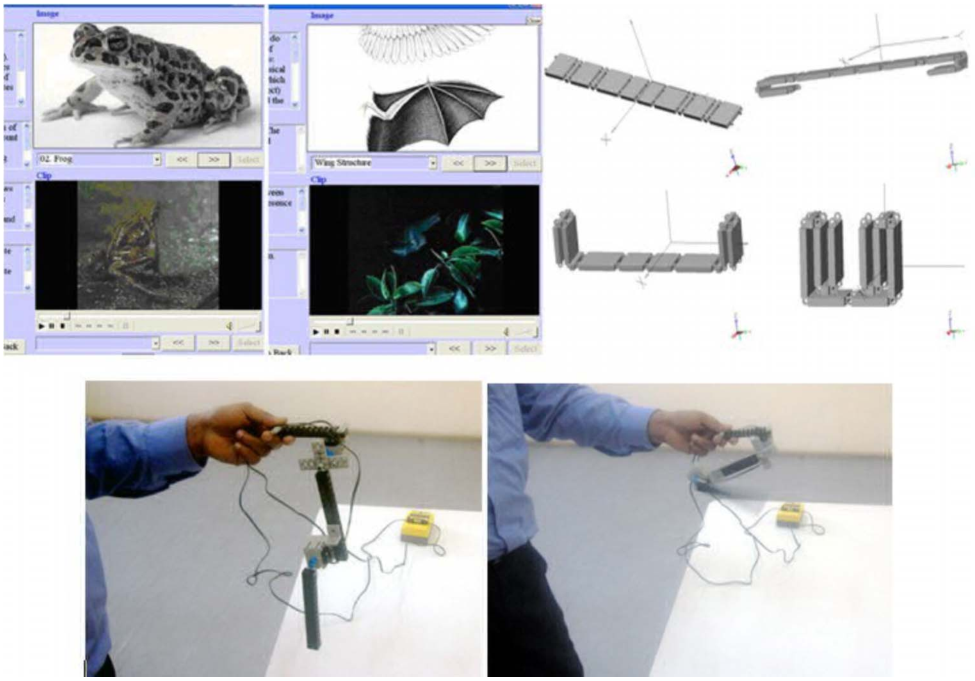


Fig. 4 Frogs hind legs and Bat's wings as sources of inspiration for a foldable mechanism (top left); simulation of deployment folding mechanism (top right); physical model and sequence of operations (bottom)

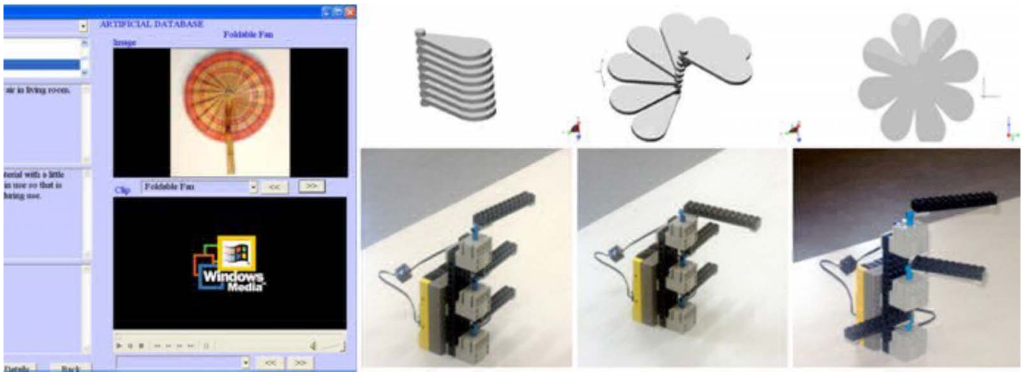


Fig. 5 Japanese fan as a source of inspiration (left); simulation and physical model of deployment (right)

3 Realization

The realization support has the following parts.

1. Virtual modeling and experimentation support, which uses SOLID WORKS™, MSC VISUAL NASTRAN™, and MATLAB's simulink™ to support simulation and experimentation of the essential subsystems in a variety of virtual environments. Each design underwent several iterations and modifications before being selected for physical modeling and experimentation.
2. Physical modeling and experimentation support uses LEGO MINDSTORMS™ robotic kit. A scaled model of the required system with the essential subsystems is modeled. In physical modeling, input values for various parameters were taken from the virtual simulations in order to test physical prototypes for functioning.

3.1 Modeling of the Entire System: A Step Toward Actual Working Prototype. The realization support helps fast experimentation with ideas using, respectively, a virtual and a physical modeling environment. Using virtual modeling first allows experimentation with a wider set of ideas faster, thereby pruning the number to a few that pass the test, while physical modeling, though time consuming, enables a justification better grounded in reality.

These experiments are used to evaluate the usefulness of the realization support. This is done in terms of how well the support helps representation of the task and the environment, aids creation of realistic solutions and their simulation in realistic environments, and the resulting inspiration it provides to designers to make the ideas more realizable.

3.2 Evaluation of Realization Support. We demonstrate the evaluation process with a case study, in which two experienced designers were given two problems to solve individually using the two-step approach and the support developed. Both designers have formal graduate training in designing and have two to three years of experience in designing engineering products in industry. Neither had any prior experience in solving the kind of problems used in the experiments described below.

In both the cases, the designers first used IDEA-INSPIRE to generate a variety of ideas for each problem, and selected some of these for further development. Then, they used the virtual modeling support to model these ideas as solutions and used virtual simulation to evaluate, modify, and select some for further development. These solutions were then modeled in the physical modeling environment for evaluation, modification, and final selection. The result is creation of product ideas that are both novel and realistic.

The problems used in the experiments were to

1. design and develop an all terrain vehicle that can travel in air, on the ground and under water. The vehicle needs to take appropriate routes based on the presence and size of an obstacle and
2. design and develop a remotely controlled deployable mechanism for a solar panel for use in space. The area of the solar panel should be as large as possible and the entire system should be foldable in the least amount of space.

By inspecting the entries retrieved (e.g., bee, rockets, etc.) from IDEA-INSPIRE, each designer was able to generate a variety of initial solutions (see Fig. 2). Each problem was expressed using various verb-noun-adjective combinations, e.g., $\text{move}(V)+\text{solid}(N)+\text{medium}(A)$ or $\text{none}(V)+\text{motion}(N)+\text{none}(A)$. The software retrieved many entries, and the designers generated various ideas for solving the problem by taking various aspects of these entries. The

Table 2 Statistics on the problems solved (D1, D2: designers; VS/PS: virtual/physical simulation)

	No. of solutions generated during ideation	Time taken in hours for ideation (h)	No. of solutions chosen for VS	No. of iterations during VS	Time taken for VS (h)	No. of solutions chosen for PS	No. of iterations during PS	Total amount of time for PS (h)
				Problem 1				
D1	5	2	1	4	15	1	3	3
D2	6	2.5	2	3	12	1	3	3
				Problem 2				
D1	11	3	2	3	10	2	3	4
D2	5	1.5	1	2	4	1	1	2

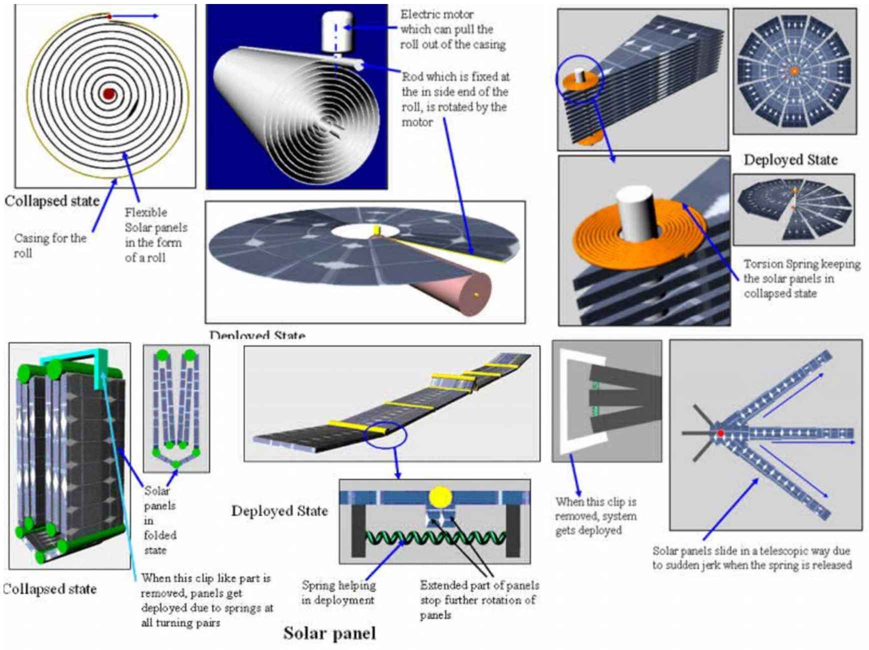


Fig. 6 Some of the initial intended systems

entries retrieved by the software were from both artificial and natural domains. From the natural domain, some of the ideas retrieved were bee, butterfly, housefly, and locust. From the artificial domain, some ideas retrieved were rocket, steam engine, disk brakes, and cam mechanism. One such entry is shown in the Appendix. Next, designers selected some of these ideas, modeled them, simulated them in different environmental conditions, and modified, leading to their progressive pruning to those which in modified form fulfilled the requirements of the design to their satisfaction.

3.3 Virtual Modeling and Simulation. The first solution is an all-terrain, all-medium vehicle, with four wheels to maneuver on land, an inflatable balloon to use as ballast to go down under water, and a set of deployable legs to enable walking avoiding small obstacles on land or under water.

Fig. 7 An all terrain vehicle

Virtual modeling and simulation were carried out in steps. Motion on land and obstacle avoidance were part of the simulation. Pressure sensors were attached to different parts of the vehicle, aiding obstacle avoidance. A motor was attached to each wheel and the constraints between the wheels of the vehicle and the ground plane were specified. Rotation of the wheels was controlled by using MATLAB's simulink™. In another version, the vehicle had a proximity sensor and avoided obstacles without colliding on them (see Fig. 3). Inputs were taken from IDEA-INSPIRE for modification, as required.

The designers created two more solutions which were also virtually modeled, simulated, and made into physical prototypes; the first one used inspiration from a *millipede* and for the second one from a leech.

3.4 Physical Modeling and Simulation. Dimensions of the components and values of the variables (e.g., frictional force required, torque at the wheels, placement of sensors, etc.) were finalized during virtual simulation. Taking these values, physical modeling of the designs was carried out using LEGO MINDSTORMS™ building blocks. The modeled designs were controlled by RCX, a programmable device, which is part of the LEGO MINDSTORMS™ kit.

For the second problem, the designers followed a similar sequence of steps as in the first problem. Using IDEA-INSPIRE software, they generated initial solutions and selected some of these,

Fig. 8 Use of different systems of an all terrain vehicle

which they modeled using the modeling support. Then, simulation was carried out using inputs from IDEA-INSPIRE and from designers themselves. The final selected solutions were modeled, simulated, and developed into physical prototypes (see Figs. 4 and 5 for the source of inspiration, simulations and physical prototypes, and the intended resulting design for two such solutions).

Table 2 shows the number of solutions generated in the problems solved, and the amount of time spent in ideation, visualization, and evaluation of these solutions for various stages of development of the ideas. Designers were able to generate, explore, and evaluate some 27 initial solutions in a span of 9 h (about 20 min per idea). They could model, explore, and modify the six solutions selected, on the virtual environment, in 41 h (about 6.83 h per solution), and finally model, explore and modify the six solutions selected in a span of 12 h (average 2.4 h). Together five realistic solutions were developed during a course of 62 h (just under 8 working days). On an average it took 3.4 h for each virtual iteration and 1.2 h for each physical iteration. From our own experience of developing industrial products, we believe that this could be considered as a fast ideation-realization process.

Note that some of these designs already exist (like the fan model for deployment of solar panels, which was designed for Phoenix Mars Lander [31]). However, the fact that the designers, with no experience or interest in this domain of design, ignorant to prior existence of these designs, were still able to generate them independently is a testimony to the support of creativity provided by the methodology. This personal creativity or *p*-creativity as described by Boden [32], which means the ability to create an idea that is novel to the individual generating it, is an essential prerequisite to the eventual desirable *s*-creativity or societal creativity [32] where ideas are novel to the entire society.

Apart from these design experiments, many other designers have used the software to generate solutions for their own design problems (which were not physically modeled), such as design of a space station repair vehicle (used inspiration from leech that can stick to the wall or hang and move even in the absence of gravity), control of high temperature, high pressure fluid flow (used inspiration from the various valves found in animal bodies and in water supply circuits), and cutting mechanisms (used inspiration from various cutters used in machine shops as well as from barnacles and sunflower).

The two-step approach described in this paper supports both "generative variation" (through ideation) and "adaptive variation" (through realization), as described by Fricke [33] as two major strategies of designers for solution generation. Generative variation has been found by earlier researchers to enhance novelty of solutions by enabling exploration of a large space of ideas, while adaptive variation enables their consolidation and optimization, making them more implementable and realistic, as emphasized by Thompson and Lordan [34]. The overall effect is development of ideas with both novelty and realizability. Some of the initial designs for Problem 2 (Sec. 3.2) are in Fig. 6.

3.5 Learning From Modeling and Simulation. A number of instances of learning took place during use of the modeling support. In most of the cases, designers used the details provided in the relevant entries from IDEA-INSPIRE. Some of the things designers learned about during simulation are as follows.

Friction and restitution coefficients necessary for a car to move freely on the ground.

The linear momentum with which the car should collide with the obstacle so that the touch sensor would be actuated but the car would not undergo serious deformation, and the extent to which the wheels of a car should rotate for it to avoid obstacles.

Legs of a vehicle need a mechanism similar to feet, which must be dynamically balanced, else it could not move forward or retract. This led to exploration of several ways by which the body of the vehicle can be dynamically balanced.

For this mechanism to perform appropriately, the motion of the legs must follow an appropriate sequence.

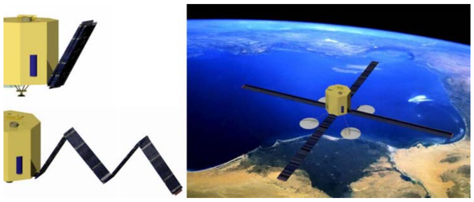


Fig. 9 Solar array deployment (left) and deployed condition in intended situation (right)

3.6 Modeling of the System. It can be noticed from Figs. 4 and 5 that even though the systems are realized, the structural components still do not represent the actual system. So, the selected solutions, including their major subsystems, are further modeled using CAD software. These models are explained next. The solution for Problem 1 (Fig. 7) is an all terrain vehicle. Figure 7 shows its major components (see Fig. 8 for the simulated model).

The major components are a *balloon* for flying in air and two cylindrical *chambers* that can be filled with water to control the vehicle to be at various heights in water. A set of deployable *wheels* enables it to run on ground. The deployable walking *legs* help it to climb over big obstacles and walk on river bed, clinging to something when the water current is high. Figure 8 shows the use of its major subsystems in different situations.

Two solutions for Problem 2 (Figs. 9 and 10), earlier modeled in Figs. 4 and 5, are two solar array deployment systems with the main structural components modeled.

Modeling the entire system gives a framework for further design and more detailed modeling by domain experts. Physical modeling provides a more concrete form to each solution. The final system, being complex, cannot be tested before an actual prototype is developed, requiring many hours of subsystem modeling by experienced engineers.

In an earlier work done by Sarkar and Chakrabarti [35], various novelty measuring methods have been reviewed, and a new method for measuring creativity has been proposed and evaluated. This method uses novelty and usefulness of a product to determine creativity of the product. Using this method one can categorize the novelty of products into four groups: very highly novelty (its function itself is novel), high novelty (input and state changes used by the product are novel), medium novelty (physical phenomena or effects used are novel), and low novelty (organs or parts used are novel). We have found that the ideas generated in the cases studied in this paper are in high and medium novelties.

4 Conclusions

We hope to have demonstrated that systematic use of knowledge from both artificial and natural domains can not only help designers to generate a variety of solutions but also aid in their development into realizable and practical prototypes. Using experimental studies of engineering designers we explained the workings of a biomimetics-based framework for systematic support for designers to develop novel realizable engineering solu-

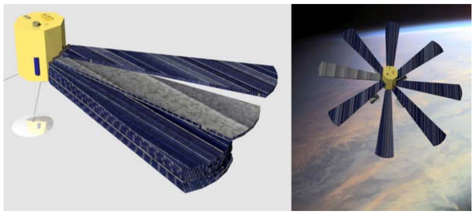


Fig. 10 Solar array deployment (left) and deployed condition in intended situation (right)

The bees fly in order to transport themselves from place to place in search of food. They mainly consume nectar of the flowers.

Bees have two muscle systems to enable flight. Direct Muscle System and Indirect Muscle System. The figure shows the double-hinged attachment of the wings to the thorax, one hinge being connected to the side of the thorax (outer hinge) and the other to the tergum (inner hinge). The dorsoventral muscles, running from the tergum to the bottom of the thorax.

The Bees employ the Indirect Muscle system. The dorsoventral muscles, running from the tergum to the bottom of the thorax, contract to raise the wings. (Starting from the image at the bottom). When the dorsoventral muscles contract, the tergum is lowered and the wings rotate about the outer hinges and rise. The longitudinal muscles, running along the length of the thorax, contract to lower the wings. When the

The bees are very good at flying. It is interpreted as a change of state from rest to flight. This can be discussed as follows: The dorso-ventral muscles (part) contracts (physical phenomenon). This is due to the contracting force (input), which activates the hooks law (physical effect) and it requires the presence of link between the wing and the body (organ). The wing (part) rotates in the clockwise direction (physical phenomenon). This is due to the

To fly from one place to another. To move from one place to another.

The contracting force. The moment applied. The contracting force. The moment applied. The electrical signals.

The dorso-ventral muscles contracts. The wing rotates in the clockwise direction. The longitudinal muscle contracts.

link between the wing and the body. link between the wing and the muscle. link between the wing and the body. link

Hooks law. Lever effect.

Dorso-ventral muscles.

The insect is at rest. The insect is flying.

Fig. 11 An entry from the database

tions using inspiration from natural and artificial domains. The methodology and support developed should help engineering designers to use inspiration from nature in order to generate products as solutions to engineering problems and then develop them into practical prototypes. Indian Space Research Organization (ISRO) has delivered IDEA-INSPIRE to help its designers to generate suitable products for space applications. A customized version of IDEA-INSPIRE is also delivered to the innovation wing of a global engineering conglomerate to inspire their designers in ideation.

Acknowledgment

The authors acknowledge the help rendered by the designers who participated in the evaluation of the methodology. Microsoft™ is registered to Microsoft Corporation. SOLID WORKS™ is a registered to SolidWorks Corporation. MSC VISUAL NASTRAN™ is registered to MSC.Software Corp. LEGO MINDSTORMS™ is registered to Lego group. MATLAB's simulink™ is registered to Mathworks, Inc. ISRO supported earlier development of this methodology. All authors contributed equally to this work and declare no competing financial interest.

Appendix: Example Showing Human Understandable (FBS and SAPPhIRE Model) Codes for an Entry (Bee) in the Database

FBS

Function. Bees fly in order to transport themselves from place to place in search of food. They mainly consume nectar of the flowers.

Structure. Bees have two muscle systems to enable flight: direct muscle system and indirect muscle system. Figure 11 shows the double-hinged attachment of the wings to the thorax, one hinge being connected to the side of the thorax (outer hinge) and the other to the tergum (inner hinge). The dorsoventral muscles run from the tergum to the bottom of the thorax.

Behaviour. The bees employ the indirect muscle system. The dorsoventral muscles, running from the tergum to the bottom of the thorax, contract to raise the wings (starting from the image at the bottom). When the dorsoventral muscles contract, the tergum is lowered and the wings rotate about the outer hinges and rise. The longitudinal muscles, running along the length of the thorax, contract to lower the wings. When the longitudinal muscles contract, the tergum is forced upward again, and the wings rotate in the opposite sense about the outer hinges. The effect of the indirect musculature may be described by a familiar object: the tennis ball.

SAPPhIRE Constructs

- Action
  - To fly from one place to another.
  - To move from one place to another.
- State
  - The insect is at rest.
  - The insect is flying.
- Phyphenomenon
  - The dorsoventral muscles contract.
  - The wing rotates in the clockwise direction.
  - The longitudinal muscle contracts.
  - The wing rotates in the counterclockwise.
  - The wing movements are monitored by the brain.
- Phyeffect
  - Hooks law.
  - Lever effect.
- Input
  - The contracting force.
  - The moment applied.
  - The electrical signals.
- Organ
  - Link between the wing and the body.
  - Link between the wing and the muscle.
  - Link between brain and body.
- Parts
  - Dorsoventral muscles.

For an example of Machine-understandable codes for an entry, see [4].

References

[1] MONGABAY™, http://news.mongabay.com/2005/0711-rhett-butler.html.
[2] Vogel, S., 1992, *Vital Circuits*, Oxford University Press, Oxford.
[3] Vogel, S., 1998, *Cat's Paws and Catapults: Mechanical Worlds of Nature and People*, Norton, New York.
[4] Chakrabarti, A., Sarkar, P., Leelavathamma, and Nataraju, B. S., 2005, "A Functional Representation for Biomimetic and Artificial Inspiration of New Ideas," Artif. Intell. Eng. Des. Anal. Manuf., **19**, pp. 113–132.
[5] BIONICS™, http://en.wikipedia.org/wiki/bionics.
[6] Benyus, J. M., 1997, *Biomimicry: Innovation inspired by nature*, Quill.
[7] David, G., 1994, "Synthetic Spider Silk," Technol. Rev., **97**(7), pp. 16–17.
[8] Murakami, T., and Nakajima, N., 1997, "Mechanism Concept Retrieval Using Configuration Space," Res. Eng. Des., **9**, pp. 9–11.
[9] Kletke, M. G., Mackay, J. M., Barr, S. H., and Jones, B., 2001, "Creativity in the Organization: The Role of Individual Creative Problem Solving and Computer Support," Int. J. Hum.-Comput. Stud., **55**, pp. 217–237.
[10] MacCrimmon, K. R., and Wagner, C., 1994, "Stimulating Ideas Through Creative Softwares," Manage. Sci., **40**, pp. 1514–1532.
[11] Watson, D. L., 1989, "Enhancing Creative Productivity With the Fisher Associated Lists," J. Creat. Behav., **23**, pp. 51–58.
[12] Bhatta, S., Goel, A., and Prabhakar, S., 1994, "Innovation in Analogical Design: A Model, Based Approach," *Proceedings of the AI in Design*, Kluwer

Academic, Dordrecht, The Netherlands, pp. 57–74.

[13] Qian, L., and Gero, J. S., 1996, “Function-Behavior-Structure Paths and Their Role in Analogy-Based Design,” Artif. Intell. Eng. Des. Anal. Manuf., **10**(4), pp. 289–312.

[14] Gordon, W. J. J., 1961, *Synthesis: The Development of Creative Capacity*, Harper & Row, New York.

[15] Gentner, D., 1983, “Structure Mapping—A Theoretical Framework,” Cogn. Sci., **7**, pp. 155—177.

[16] Chiu, M., 2003, “Design Moves in Situated Design With Case-Based Reasoning,” Des. Stud., **24**, pp. 1–25.

[17] Gentner, D., and Markman, A. B., 1997, “Structure Mapping in Analogy and Similarity,” Am. Mineral., **52**, pp. 45–56.

[18] Blanchette, I., and Dunbar, K., 2001, “Analogy Use in Naturalistic Settings: The Influence of Audience, Emotion, and Goals,” Mem. Cognit., **29**(5), pp. 730–735.

[19] Larry, W., Zimmerman, P. E., and Hart, D. G., 1988, *Value Engineering: A Practical Approach for Owners, Designers and Contractors*, CBS, New Delhi.

[20] Hacco, E., and Shu, L., 2002, “Biomimetic Concept Generation Applied to Design for Remanufacture,” *Proceedings of 2002 ASME Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Montreal, Canada, Sept. 29–Oct. 2, Paper No. DETC 2002/DFM-34177.

[21] Shu, L. H., Lenau, T. A., Hansen, H. N., and Alting, L., 2003, “Biomimetics Applied to Centering in Microassembly,” CIRP Ann., **52**(1), pp. 101–104.

[22] Shu, L., 2004, “Generalizing the Biomimetic Design Process,” *Canadian Design Engineering Network Design Conference*, Montreal, Quebec, July 29–30.

[23] Vakili, V., and Shu, L., 2001, “Towards Biomimetic Concept Generation,” *Proceedings of 2001 ASME Design Technical Conferences, Design Theory and Methodology Conference*, Pittsburgh, PA, Sept. 9–12, Paper No. DETC2001/DTM-21715.

[24] Chakrabarti, A., and Bligh, T. P., 2001, “A Scheme for Functional Reasoning in Conceptual Design,” Des. Stud., **22**(6), pp. 493–517.

[25] French, M. J., 1998, *Invention and Evolution: Design in Nature and Engineering*, CUP, Cambridge.

[26] Sefertzi, E., 2000, Report Produced for the EC Funded Project Innoregio: “Dissemination of Innovation and Knowledge Management Techniques.”

[27] Csikszentmihalyi, M., 1997, *Creativity: Flow and the Psychology of Discovery and Invention*, Harper Perennial.

[28] Sternberg, R. J., and Lubart, I. T., 1999, “The Concept of Creativity: Prospects and Paradigms.” in *Handbook of Creativity*, R. J. Sternberg, ed., Cambridge University Press, Cambridge.

[29] McClelland, D. C., 1988, *Human Motivation*, 3rd ed., Cambridge University Press, Cambridge.

[30] Sarkar, P., and Chakrabarti, A., 2008, “Studying Engineering Design Creativity,” Invited Paper in the *Proceedings of the NSF Workshop on Studying Design Creativity*, J. Gero, ed., Aix-en-Provence, France, March.

[31] FOURTH-MILLENNIUM™, http://www.fourth-millennium.net/space-exploration/space-exploration-phoenix.html.

[32] Boden, M. A., 1999, “Computer Models of Creativity” in *Handbook of Creativity*, R. J. Sternberg, ed., Cambridge University Press, Cambridge.

[33] Fricke, G., 1992, *Proceedings Research in Design Thinking*, N. Cross, K. Dorst, and N. F. M. Roozenburg, eds., Delft University Press, Delft, pp. 105–109.

[34] Thompson, G., and Lordan, M. M., 2001, “Experience of Creativity Enhancement Teaching in Industry and University” *International Conference on Engineering Design ICED’01, Glasgow*.

[35] Sarkar, P., and Chakrabarti, A., 2007, “Development of a Method for Assessing Design Creativity,” *International Conference on Engineering Design, ICED 2007*.