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DEVELOPING NOVEL TECHNICAL SYSTEMS USING IDEAS FROM NATURE

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ABSTRACT
The transfer of technology between life forms and synthetic constructs is desirable because evolutionary pressure typically forces natural systems to become highly optimized and efficient. Biomimicry is a science that studies nature's ideas to imitate these to solve human problems. A few examples of bio inspired systems in engineering are hulls of boats imitating the thick skin of dolphins, sonar, radar, and medical ultrasound imaging imitating the echolocation of bats. In the field of computer science, bio-mimicry has produced cybernetics, artificial neurons and artificial neural networks. Vincent [1] 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. However, there is no general, systematic support available for engineering designers to use nature as inspiration for solving design problems – right from *ideation* to *realisation* of ideas. We have developed such a support and evaluated it using designers for its ability to inspire them to develop novel and feasible products.

To support ideation, two databases are developed with entries having information about natural and artificial systems. A novel, generic causal model is proposed for structuring information of how these systems achieve their behaviour. Three algorithms are developed for analogical search of entries that could inspire ideation of solutions to a given problem. In realisation, evaluation and modification of these solutions are carried out by experimenting with these in virtual and physical forms and environments.

Keywords: Bio mimicry, idea generation

1 INTRODUCTION
Nature, through billions of years of trial and error, has produced effective solutions to innumerable, complex, real-world problems [2]. 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. Some such examples are:

- Velcro resulted in 1948 from a Swiss engineer, George de Mestral, noticing how the hooks of the plant burrs stuck in the fur of his dog [2].
- A research team at Bell Labs found that tropical deep-sea sponge Euplectella, or Venus's flower basket, builds remarkably strong structures from extremely fragile materials. This discovery led to unique insights in the production of commercial fibre optic strands [2].
- DaimlerChrysler is developing a new high fuel efficiency concept vehicle based on the body shape of a boxfish, a common cube-shaped fish found in tropical marine habitats. The bionic car will offer 20 percent lower fuel consumption and up to 80 percent lower nitrogen oxide emissions [2].

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 [3]. The question is: how to use systematically the knowledge of these systems to solve design problems?

2 METHODOLOGY
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.

2.1 Ideation
Generating a large number of ideas with a variety of principles [4] increases the chances of developing better products [5]; experimenting with ideas in realistic environments makes them more practically viable. Creative products are initiated through inspiration [6-7], where use of analogy is beneficial [8-11].

Analogy has long been regarded as a powerful means for inspiring novel idea generation, as seen in several systems based on analogy [9], and creativity methods developed with the specific aim of fostering analogical reasoning [11]. The overall objective in ideation is to use analogical reasoning with a functional/behavioural language to get inspirations for ideas to a given design problem.

The proposed support for inspiring ideation 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, behaviour or structure, ideation should be enhanced. We did this by developing:
- Two databases of natural and artificial systems.
- A generic model to represent the behaviour of each entry in the database (SAPPhIRE Model of causality).
- Algorithms for analogical search of entries from these databases for a given design problem, and then presenting these to designers for inspiration using a piece of software called 'Idea-Inspire' that has been developed by us.

2.2 Realization
The support has the following parts:

1. Virtual modelling and experimentation support, which uses Solid Works^{TM} and MSC Visual Nastran^{TM} and Matlab's simulink^{TM} to support simulation and experimentation of the essential sub-systems in a variety of virtual environments. The designs undergo several iterations and modifications, before being selected for physical modelling and experimentation.

2. Physical working modelling and experimentation support, which uses Lego Mindstorms^{TM} robotic kit. A scaled model of the required system with essential sub systems is modelled. Once physical modelling is completed, input values of various parameters are taken from the virtual simulations to test physical prototypes for functioning.

3. Modelling of the entire system, a step towards actual working prototype.

3 RESULTS
Results are twofold: the resulting support for –'ideation', and that for 'realization'.

3.1 Ideation
The database developed [3] has over 700 entries containing natural (e.g., insects) and artificial systems (e.g. vacuum cleaners). A generic, causal model for describing the behaviour of each entry in the database is developed. The constructs used in the model are:

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.

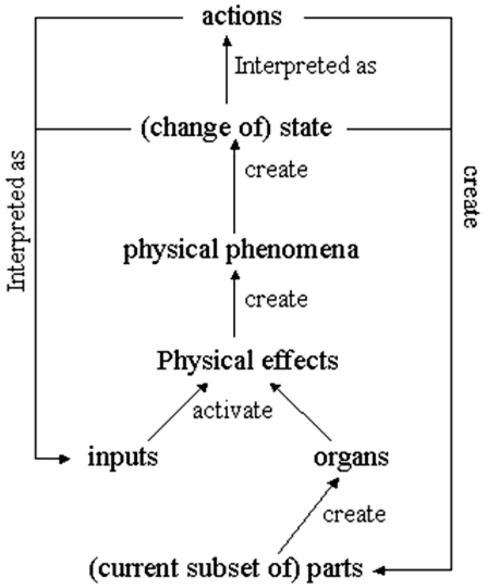

Fig 1. The Sapphire Model of Causality.

These constructs are linked using three relationships: activation, creation and interpretation. Parts create organs. Organs and inputs activate physical effects. When activated, physical effects create physical phenomena and changes of state. Changes of state are interpreted as actions or inputs, and create or activate parts. The model is termed SAPPhIRE model, where SAPPhIRE is an acronym for State-Action-Part-Phenomenon-Input-oRgan-Effect (Fig.1). Each entry (e.g., in Fig. 2) in the database is described using a linked list of SAPPhIRE constructs.

Fig 2. An Entry from the Biological Database.

Ideation is supported by a software called ‘Idea-Inspire’ [3], developed by us, that searches for analogical entries in the database to stimulate ideation of potential solution alternatives. A designer, with a problem to solve, would describe the problem in terms of the constructs of the ‘SAPPhIRE’ model (Fig.1) – and the software would search for entries in the databases that are analogically similar to this.

Three search algorithms are developed for this purpose.
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.

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 fulfil a given, required action, or entries that have analogical parts to those having the required action.

Ideation effectiveness of the support was evaluated in two stages. In the first, preliminary stage, three designers were asked to individually generate as many ideas as possible to solve three design problems. They were then asked to generate further ideas taking inspiration from entries in 'Idea Inspire'. On an 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. In the second stage, twelve designers were offered support of ideation in their respective design problems. Their feedback showed consistent results in terms of enhancement of the number of ideas generated (as in the preliminary evaluation) as well as confirmed ease of usability of the software. This, however, does not support attainment of realisability of these ideas – an essential aspect of engineering product development. For this, realisation support was developed, and used in another study, where working prototypes to embody these ideas are created.

Table 1. Efficacy of software (from [1])

	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 G2/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 %

3.2 Realization

The realization support helps fast experimentation with ideas using, respectively, a virtual and a physical modelling environment. Virtual modelling first allows experimentation with a wider set of ideas faster, thereby pruning the number to a few that pass the test; while physical modelling, though time consuming, enables a justification better grounded in reality.

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

We demonstrate the evaluation process with a case study, in which two designers were given two problems to solve individually using the two step approach and the support developed. They 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 modelling support to model these ideas as solutions, and used virtual simulation to evaluate, modify and select some for further development. These solutions are modelled in the physical modelling 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 a vehicle that can travel in ground and under water. The vehicle needs to take appropriate routes based on the presence and size of an obstacle.
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.

While searching for solutions using Idea-inspire the designers have used various search strategies and used various combinations of verb, noun and adjectives for searching for suitable solutions. For example to solution for problem 1, designers have searched for 'move+ mass + (in) water' or 'avoid + object' and for problem 2 'deploy' or 'open + object '. Searching the databases resulted in many entries which have inspired the designers to generate suitable solutions. By inspecting the entries retrieved (e.g., Bee, Rockets, etc) from 'Idea-Inspire', the designers were able to generate a variety of initial solutions. Next, they selected some of these, modelled them, simulated them in different environmental conditions, and modified, leading to their progressive pruning to those which in their modified form satisfy the requirements of the design.

3.3 Virtual modelling and simulation

The first solution is an two-terrain, two-medium vehicle, with four wheels to manoeuvre on land, an inflatable balloon to go down under water (by using the balloon as ballast), and a set of deployable legs to enable walking avoiding small obstacles on land or under water.

Virtual modelling and simulation was carried out in steps. Motion on land and obstacle avoidance were parts 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^{TM}'. 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.

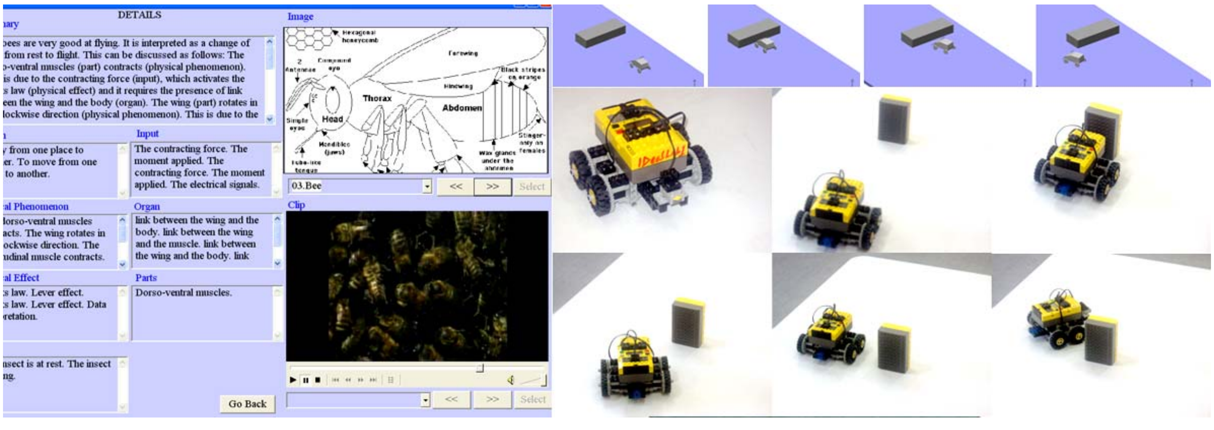

Fig 3. Shows an entry of a bee as the source of inspiration (left), simulation of the intended vehicle (Moving forward, colliding with the obstacle, retracting after collision, taking a left turn to avoid the obstacle, and the physical modeling how it avoids the obstacle (right).

Designers have selected two more solutions which they virtually modelled, simulated and physical prototype were developed; the first one using inspiration from a millipede and for the second from a leach.

3.4 Physical Modelling and Simulation

Dimensions of the components and values of the variables (e.g., frictional force required, torque at the wheels, placement of sensors, etc) are finalized during simulation. Taking these values, physical modelling of the designs was carried out using Lego Mindstorms™ building blocks. The modelled designs were controlled by RCX, a programmable device which is part of Lego Mindstorms™ Kit (Fig. 4 shows one such physical model).The intended solution is shown in Fig. 2.

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, which they modelled using the modelling support. Then, simulation was carried out using inputs from 'Idea-Inspire' and from the designers. The final selected solutions were modelled, simulated and physical prototypes developed (see Fig. 4 and 5 for source of inspirations, simulations, physical prototypes and the intended resulting design for two such solutions).

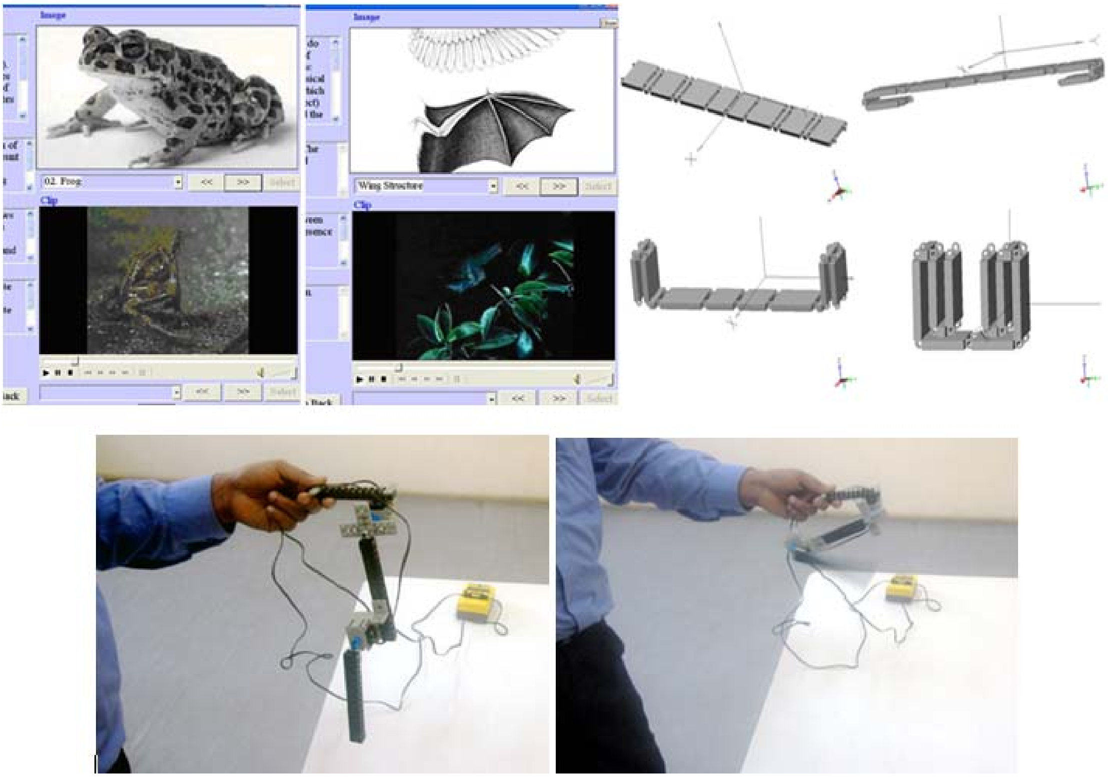

Fig 4. Frogs hind legs and Bat's wings as sources of inspiration for a foldable mechanism (Top Left). Simulation of deployment folding mechanism (Top Right). Physical Model and sequence of operations (Middle).

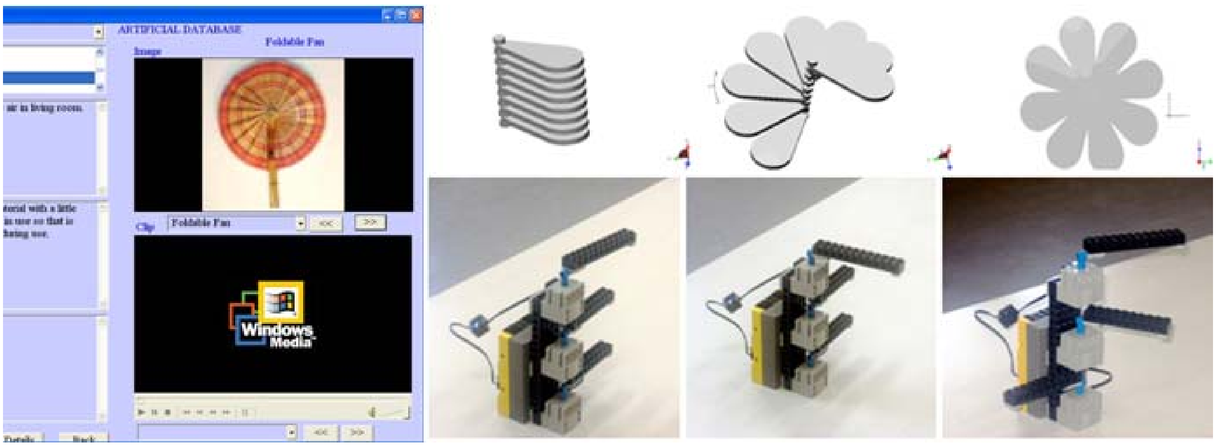

Fig 5. Japanese fan as a source of information (left). Simulation and Physical Model of deployment (right)

Table 2 shows some statistics about the number of solutions generated in the problems solved, and the amount of time spent in 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 hours (about 20 min. per idea). They could model, explore and modify the 6 solutions selected, on the virtual environment, in 41 hours (about 6.83 hours per solution), and finally model, explore and modify the 5 solutions selected in a span of 12 hours (average 2.4 hours). Together 5 realistic solutions were developed during a course of 62 hours (just under 8 working days). On an average it took 3.4 hours for each virtual iteration, and 1.2 hours for each physical iteration. This should be recognized as a fast ideation-realization process, as creation of a variety of ideas and turning them into realistic solutions currently requires a substantially longer period of time in industry.

Table 2 Data of the problems solved

	No of ideas generated	Time required for generating solutions	No of ideas selected for virtual modelling	No. of iterations	Time required	No of models selected for Physical modelling	No. of iterations	Time required for physically modelling them
Problem 1								
Designer 1	5	2	1	4	15	1	3	3
Designer 2	6	2.5	2	3	12	1	3	3
Problem 2								
Designer1	11	3	2	3	10	2	3	4
Designer 2	5	1.5	1	2	4	1	1	2

Note: Time in shown in hours (approximate).

Apart from these design experiments, many other designers have used the software to generate solutions for their design problems (which were not physically modelled), such as design of a space station-repair vehicle (uses 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 (uses inspiration from the various valves found in animal bodies and in water supply circuits) and cutting mechanisms (uses inspiration from various cutters used in machine shops as well as from barnacles and sunflower).

The two step approach described and demonstrated in this paper supports both ‘generative variation’ (through Ideation) and ‘adaptive variation’ (through Realization), as described by [12] as two major strategies of designers for solution generation. Generative variation enhances novelty of solutions by enabling exploration of a large space of ideas; modification variation enables consolidation and optimization of these ideas, making them more implementable and realistic, as emphasized in [13]. The overall effect is development of ideas with both novelty and realizability.

4 MODELLING OF ENTIRE SYSTEM

It can be noticed from Figures 4 and 5 that even though the systems are realized, the structural components do not represent the actual system. So, the selected solutions are modelled using CAD software. Next, the major sub systems that are required to be present in each of these systems are also modelled. These models are explained below.

Solution for problem 1(see Fig. 6): An all terrain vehicle has been modelled. Fig 6 shows all the major components of it (also see fig. 3 for the simulated model).

The major components as seen are balloon for flying in air, two cylindrical chambers that can be filled with water which decides whether the vehicle will be on the surface of the water or under water like a sub marine. 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. Fig 7 shows the use of its major sun systems in different situation.

Fig. 6. An all terrain vehicle

Fig. 7. Use of different systems of an all terrain vehicle

Solution for problem 2(Fig. 8-9): Solar array deployment system is devised with all major components. The solutions as shown in Fig. 4-5 are modelled with their intended structural components.

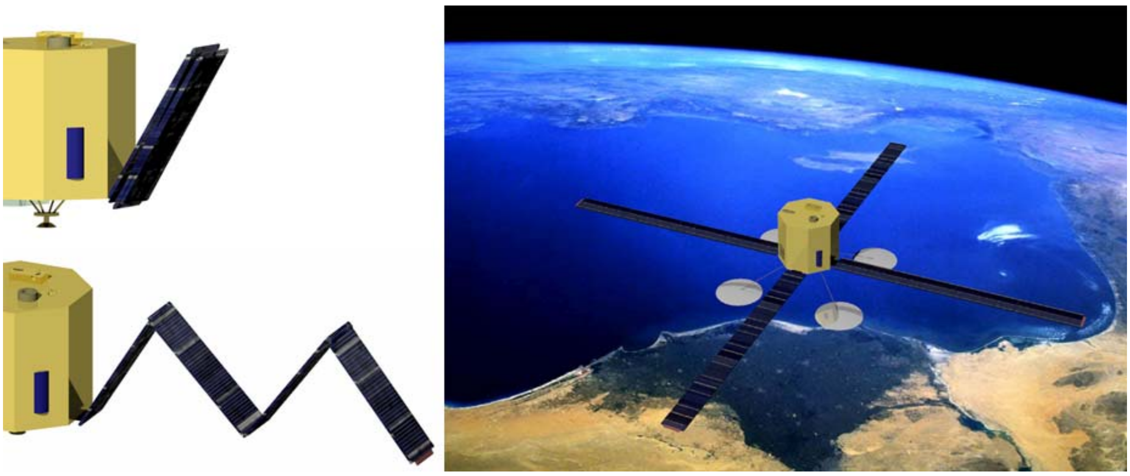

Fig 8. Solar array deployment (left) and deployed condition in intended situation (right).

Modelling the entire systems gives a structural framework for further design and detailed modelling by domain experts. Physical modelling delivers a more concrete form to a solution. The final system being complex, cannot be tested before actual prototype is developed, requiring many hours of sub system modelling by experienced designers.

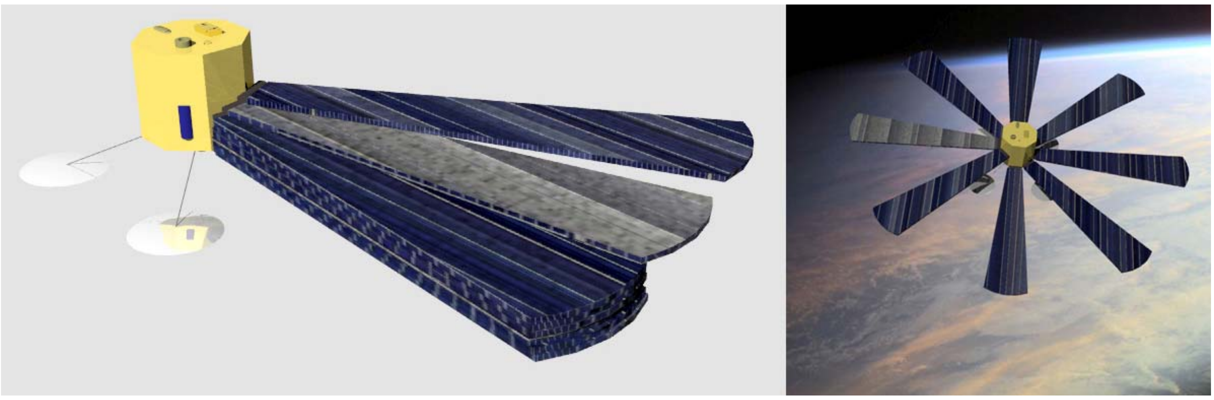

Fig 9. Solar array deployment (left) and deployed condition in intended situation (right).

5 CONCLUSIONS

We have demonstrated that systematic use of knowledge from both artificial and natural domains can not only help designers to generate a large variety of solutions, but also aid in their development into realizable prototypes. Using experimental study of engineering designers we are able to demonstrate that this work provides a Biomimetics-based framework for systematic support for designers to develop novel, realizable engineering solutions using inspiration from natural world.

Engineering designers can now use the developed methodology to generate products as solutions for engineering problems and then develop them into practical working prototypes using inspiration from nature.

6 ACKNOWLEDGEMENT

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REFERENCE

[1] Http://en.wikipedia.org/wiki/bionics, 2006.

[2] http://news.mongabay.com/2005/0711-rhett_butler.html, 2006.

[3] A. Chakrabarti, P Sarkar, Leelavathamma and B.S. Nataraju, A Functional Representation for Biomimetic and Artificial Inspiration of New Ideas, 2005, AIEDAM, 19, 113-132, CUP.

[4] A Gelsey, M Schwabacher and D Smith. Using modeling knowledge to guide design space search, In John S. Gero (Eds.) AI in Design, , 1996p 367-385.

[5] P Langdon and A Chakrabarti. Browsing a large solution space in breadth and depth, ICED 1999, Munich, August 24-26,1999.

[6] W. Larry, P.E. Zimmerman. and D Glen Hart. Value Engineering -a practical approach for owners, designers and contractors, CBS, 1988, ISBN no. 0-442-29587-1.

[7] Kletke Marilyn, G. Mackay Jane, M. Barr Steve, H. & Jones Beata. Creativity in the organization: the role of individual creative problem solving and computer support. Int. J. Human-Computer Studies, 55,2001, pp. 217-237

[8] S. Vogel,. Cat's Paws and Catapults: Mechanical Worlds of Nature and People, 1998 (Norton, NY).

[9] Bhatta, S. Goel, A. and Prabhakar, S. Innovation in Analogical Design: A Model-Based Approach. Proc. AI in Design, Kluwer Academic Publishers, 1994, Dordrecht, The Netherlands, pp. 57–74.

[10] Gordon, W. J. J. Synthesis: *The Development of Creative Capacity*, 1961, (New York: HAPPER & ROW).

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

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

[13] G. Thompson and M.M. Lordan. Experience of creativity enhancement teaching in industry and university in 13 ICED´01, Glasgow, 2001.

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