# REDUCING CONSEQUENCES OF CAR COLLISION USING INSPIRATION FROM NATURE

**Torben Lenau[1], Katharina Helten[2], Clemens Hepperle[2], Sebastian Schenkl[2], Udo Lindemann[2]**
(1) Technical University of Denmark, (2) Technische Universität München.
Lenau@man.dtu.dk

## ABSTRACT

**Biomimetic design stimulates the creative idea generation within product development by searching nature's enormous database of fine tuned solutions. The challenge for the designer is to find efficiently the solution analogies and principles that will solve the design problems. The present paper is a result of a project where researchers from two universities (Technical University of Denmark, DTU, and Technische Universität München, TUM) explored three different biomimetic design approaches namely the transfer checklist approach, the inspiration card approach and the interdisciplinary team approach.**
**The design problem was to reduce the consequences of car collision. All three approaches led to a large number of solution analogies that were then analysed amongst others regarding the structuredness and detail level of solution.**

**Keywords: Biomimetic design, idea generation, solution space.**

## MOTIVATION AND BACKGROUND

Biomimetic design is an interesting design process that stimulates the creative idea generation within product development. Nature represents an enormous database of fine tuned solutions that has been developed through billions of years of evolution. The challenge for the designer is to search in nature and find the solutions and principles that will solve the design problems. Literature reports about several different approaches including procedures and methods for how to work with biomimetics. It was our aim to explore some of the approaches using student projects to get experiences from working with the approaches.

The paper describes how a problem from the car industry – how to reduce the consequences of car collisions – can be solved using inspiration from nature. Three different approaches have been investigated, namely the transfer checklist approach, the inspiration card approach and the interdisciplinary team approach. The problem was focused to the handling of the mechanical impact when a car collides with solid objects, like another car, a wall or a tree.
The work also addresses a critique earlier raised in the discussions on another biomimetic paper at the International Design Conference in Dubrovnik 2010 (Lenau et al 2010), namely if biomimetic design was best suited for products with relation to humans, like medical devises. The question was if natural inspiration could be a valuable inspiration to mechanical problems as those found in the car industry. For this reason the car collision problem was selected.

## STATE OF THE ART

In biomimetics, engineering problems are solved by biological analogies (Benyus 1997, Vogel 1998, Mak & Shu 2004). Scientific knowledge, gained in biological research, is used for technical applications (Speck & Erb 2009). The degree of the abstraction of biomimetic solutions during the transfer from biology into engineering ranges from an exact copy of the biological system up to an analogy on the level of principles. A higher level of abstraction results in fewer boundaries for the technical realization, but also additional insights about the adopted biologic phenomena are needed (Mak & Shu 2004).
In the last years, a lot of research has been conducted in the development of biomimetic technologies and products as well as in methods, methodologies and procedural models to support biomimetic

development projects (Speck & Erb 2011). It has been demonstrated that there are many factors that favor the attractiveness of biologically inspired design but also that there are factors that might lead to problems.

One of the challenges is, that a biological model has to be identified that has the potential to be successfully transferred into a technology to solve a technical problem. To overcome that, a range of different approaches has been developed in the last years. Three classes of approaches can be distinguished: searching in databases, specially edited for biomimetics, searching in technical literature and using personal knowledge (Helten et al. 2011). Databases, mainly accessed by a comparison of a functional description of the technical problem, have been developed as papers based catalogues (e.g. Hill 1997, Lindemann & Gramann 2004) or as a software (Löffler 2009). These catalogues list natural systems or earlier developed biologically inspired concepts (Bruck et al. 2007). They may contain only biological solutions, but there are also catalogues with biological as well as technical solutions (Sarkar et al. 2008). These hybrid catalogues have a broader applicability since there exist technical solutions that are not found in nature like the wheel.

Vincent & Mann (2002) discuss an approach called BioTriz, enhancing the TRIZ-database with natural systems.

An approach using technical literature, not especially edited for biomimetic product development as a source is presented by Shu (2010): Within textbooks of biology, Shu suggest searching a function as well as synonyms in textbooks. The text book gives also a further concretization of the biological solution. Using fundamental literature such as Purves et al. (2003) has the benefit that engineers have less difficulties to understand these texts.

Approches using personal knowledge as a source for biological solutions are discussed e.g. by Löffler (2009) or Helten et al. (2011). Löffler suggests identifying natural solutions in a brainstorming session.

There are also hybrid approaches that incorporate several classes. One of them is the inspiration card method, discussed by Lenau et al. (2010). Within this methodology, the solution search is performed as following: Based on functional keywords searches for biological analogies are performed in different knowledge sources like books, scientific papers, the World Wide Web and by contacting biologists.

## METHOD AND PROBLEM DESCRIPTION

The applied research method is a form of action research (Whyte 1991) where the researchers themselves actively participate in the research process. Two research groups from different universities solved the same design problem using three different approaches, namely a transfer checklist approach (Lindemann & Gramann 2004), the inspiration card approach (Lenau 2009, Lenau et al 2010) and an interdisciplinary team approach (Helten et al. 2011).

A basic research question for the present work is if the creative idea generation in design work can be stimulated using inspiration from nature. Secondary questions include how this is done using the three different approaches and what the similarities and differences were.

## THE APPROACHES AND RESULTS

### *TRANSFER CHECKLIST APPROACH*

Gramann (2004) describes a procedural model involving so-called transfer checklists and Stricker (2006) reports a pre-selection procedure. In this paper we have chosen to name the approach involving the 2 procedures 'transfer checklist approach'. The checklist approach is an iterative approach, focusing the level of abstraction of the problem formulation (cp. figure 1). The approach was executed by an engineering student, without support by a person with a significant expertise in biology. In the first step, the goal of the search for biologic solutions is defined. The goal is described as a function.

In the next step, biological systems are allocated to the problem by using the checklist for biological associations according to Gramann (2004). This checklist contains of 177 specific functions that are attributed with associations in nature (cp. figure 2).

Subsequent, the allocated systems are analyzed regarding their suitability and possible implementation.

This evaluation was performed based on the method called "characterizing description" by Stricker (2006) to early pre-select biological effects appropriate for a technical problem. Based on a list of parameters (e.g. speed, force, etc.), applicable to describe both biological and technical systems, first the technical systems is characterized by describing the pursued specification of the parameters (e.g. *high* speed, *high* force). If the biological phenomenon is also characterized by a *high* speed and *high* force, the biological phenomenon is taken into account for further development. If only some parameters show parallel characteristics both for the technical and the biological system, it depends which level of congruence the two characterized systems show. The pre-selection method is illustrated in figure 3.

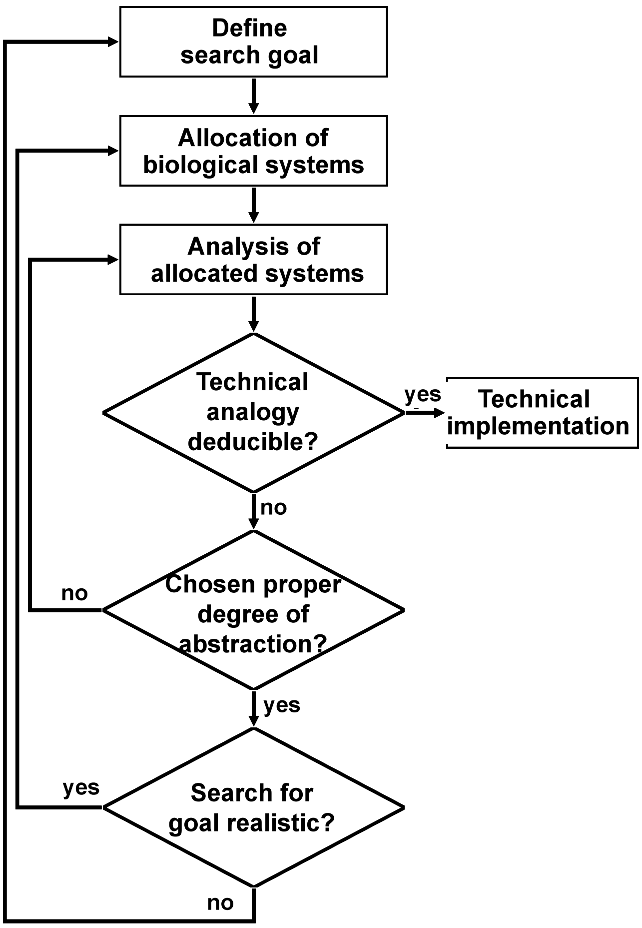


*Figure 1. Procedural model (Lindemann & Gramann 2004)*

If a technical analogy was deducible at a satisfying level of congruence, the system is implemented technically according to Gramann's procedural model (cp. figure 1). If not, the degree of abstraction of the biological system is evaluated. If the degree of abstraction was appropriate, it is checked if the goal definition is adequate as well as if the search was deep enough.

In the case study, the problem formulation for "shock absorbance / replacement for car bumpers" was abstracted as "attenuating collision impacts". Suitable functions and biological associations were identified by applying the transfer check list (cp. figure 2). The associations are listed below:

- stem
- horny skin
- combs
- intervertebral disk
- meniscus / collagen fibres

During this process, the engineering student had the challenge that only the name of the associations is given. Lacking an appropriate knowledge of biology, the student had problems gathering the working principle of the biological solutions. It was necessary to consult a textbook in biology to get more information and execute the subsequent steps.

| function I | function II | object / field / parameter | associations |
|---|---|---|---|
| modify | modify | mechanical forces | stem |
| | | torques | stem |
| | | penetration depths | callus / horny skin |
| | | pressure | - |
| | | solid (material) parameters | fiber alignment |
| | | surface parameters | squid's skin |
| measure/ identify | measure/ identify | deformation parameters | neuromuscular spindle, - |
| maintain | protect | solid elements | liquid pitch/ tree gum, comb, horny skin, spine/spike |
| | stabilyze | geometric parameters | structural bracing, chalk, silicia and chitin |
| | | deformation parameters | - |
| distribute | distribute | pressure | limbs/extremities, intervertebral disk, meniscus |
| | | forces, energies and moments | limbs/extremities, intervertebral disk, meniscus |

*Figure 2. Excerpt from the transfer checklist between technical functions and terms in biology (Gramann 2004)*

Based on the more detailed descriptions the "characterizing description" method (Stricker 2006) was applied to the five identified biological phenomena (cp. figure 3.). Therefore, first the technical problem was characterized by four suitable parameters chosen from a parameter catalogue provided by Stricker (2006). The parameters with the respective pursued specifications for the technical system are the following:

- *low* Structure Weight/size
- *high* Flexibility
- *high* Impact Force/ Structure Weight
- *high* Degree of transformation of kinetic energy into deformations

After also describing the above mentioned biological phenomena based on the four parameters, all of the five phenomena show a high congruence with the technical system. The stem, horny skin, combs and meniscus show congruence for three of the four parameters. The intervertebral disk even shows congruence in the specifications for all four considered parameters and therefore should be taken into account for the further development.

| | | Technical system | Biological phenomena | | | | |
|---|---|---|---|---|---|---|---|
| Parameter | Speci-fications | Pursued values | Stem | Horny Skin | Combs | Inter-verte-bral disk | Meniscus / Collagen Fibres |
| Structure Weight/ Size | low | O | | X | X | X | X |
| | high | | X | | | | |
| Flexibility | low | | | X | X | | |
| | high | O | X | | | X | X |
| Impact Force/ Structure Weight | low | | | | | | |
| | high | O | X | X | X | X | X |
| Degree of Transformation of Kinetic Energy into Deformations | low | | | | | | X |
| | high | O | X | X | X | X | |
| Number of congruent specifications of biological phenomenon compared to pursued specifications of technical system | | | 3 | 3 | 3 | 4 | 3 |

*Figure 3. Application of Stricker's method to preselect promising biological phenomena for the technical challenge*

As a conclusion, the student applying the methods by Gramann and Stricker detected reasonable associations for the problem of "attenuating collision impacts". As Stricker's method is only a first step to compare biological and technical systems on an abstract level, the biological phenomena have to be researched in depth in the next steps before going into detailed design. In order to detect even further appropriate biological phenomena, it is also possible to take other sources for inspiration, such as asknature.org, besides the association list of Gramann into consideration.

### *INSPIRATION CARD APPROACH*

The inspiration card approach is a five step procedure that is used to find and describe relevant biological solutions to functional problems as described in figure 4 (Lenau 2009, Lenau et al. 2010). First step is to identify the relevant functional problems and to rephrase them to make a search possible. In general this is done by formulating the functional problem in terms taken from the specific product and then generalise these formulations, for example as keywords.

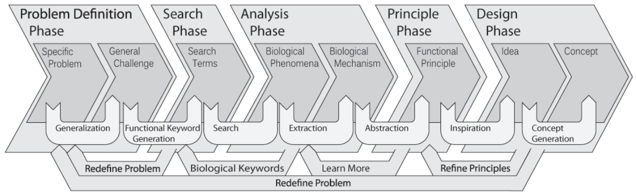


*Figure 4: Five step procedure from the inspiration card approach.*

Second step is the search for biological analogies and a number of different sources can be used: Intuitive brainstorm based on own knowledge, general world wide-web-search, the website asknature.org, dialogue with an expert (a biologist), library search based on textbooks and library search in on scientific journals. In the third step the biological analogies are analysed which is done through a literature study or by consulting relevant biologists. The fourth step is to extract the relevant information about the analogies and describe them on inspiration cards (Figure 5).

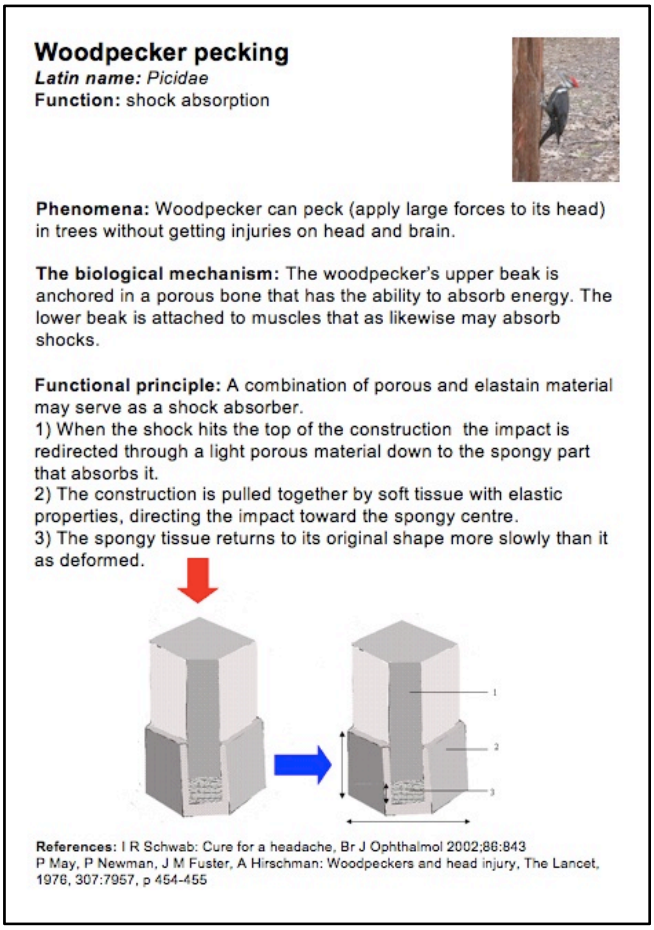


*Figure 5. Example of inspiration card for 'woodpecker pecking'*

Such a card should include the following information:

- A title describing the biological organism and the desired phenomena, e.g. Woodpecker pecking. It is an advantage to also mention the Latin name of the organism to allow for easy further information search
- A picture or drawing of the organism - preferably in action.
- A description of the phenomena using biology terminology.
- A description of the interesting principle applied in the phenomena formulated in functional engineering terms
- A simplified drawing describing the principle

Each card represents a conceptual idea and is used in the fifth step to generate design proposals.

The method was used on the collision problem by a single design-engineering student in collaboration with a biology trained librarian.

The functional problems were found to be 'Collision shock absorption, absorb energy and control deceleration'. Further keywords were found by brainstorming based on the student's own knowledge about how nature solved this type of problems. The brainstorm resulted in biological phenomena like the woodpecker pecking, the fighting of rams (male sheep and goats) and the capability of cats falling from great heights without injury. Based on the mechanisms that animals and plants use to ensure shock absorption more keyword could be formulated like 'impact AND shell, protection layer, protection mechanism, energy absorption and impact AND protection'.

These keywords were then used to search the library database and asknature.com. It was found that some of the keywords gave confusing results since they had more meanings. For example do protection mechanisms like shells have additional functions (protection from predators) so the keyword could be combined with additional keywords like 'impact' or 'shock'. A synonym dictionary could also increase the number of keywords, e.g. 'collision' have synonyms like clash, conflict, impact, crash, smash, encounter and shock.

Talks with the biology librarian expanded the results further with chicks that fall out of nests, eggs that can withstand relatively large forces and flying birds that resist large impact when landing.

The chicks that fall out of nests can manage to drop many meters down without getting injured thanks to their feathers and their elastic body.

Searching biology books like Life (Purves 2003) showed to be a little difficult. A reason could be that Life does not cover much of the macro biology where the keywords are likely to apply. A more successful search would probably require expanded considerations on the keyword formulation e.g. as described by (Shu 2010). However one book showed to be useful namely Biomechanics by Vogel (2003). It gave insight into the basic mechanisms of energy transformation in animals.

Journal articles were searched using the Biosis and Zoological records databases and gave relevant results like the surprising information that hedgehog spines also act as shock absorbers for falling animals and the energy absorption in spider webs.

The website asknature.org gave a number of relevant search results for example the energy absorbing properties of the nuchal ligament in grazing animals and the exoskeletons of dragonflies.

In total was 15 relevant biological analogies found and for each of those an inspiration card was made. Figure 5 shows one of the cards illustrating the woodpecker shock absorption principle.

Three of the cards were then used to sketch proposed solutions on a conceptual level for a car bumper: The hedgehog spine, the goat butting and the landing bird bone.

### *INTERDISCIPLINARY TEAM APPROACH*

In contrast to the two approaches mentioned before, this approach is mainly characterized by the interdisciplinary team. An engineering as well as a biology student worked together to find new biomimetic solutions. Their approach can be described as a four phase procedure, see figure 6. In phase A the engineering student defined the problem. The desired functionalities were described, followed by a first draft of principal ways to realize the functionality. In addition, search questions for the biologist were formulated referring to the main principles with the purpose to enhance the biomimetic solution finding process. In phase B the biology student looked in nature for examples and phenomena that fulfilled the required functionality - mainly through literature research, based on the student´s broad knowledge about the phenomena and the biology taxonomy. The phenomena were then presented to the engineering student with focus on the natural structure and the functionality of the objects to make them easylier understandable. In the following phase C both students discussed together iteratively about the findings. The main question was how to adapt the findings from nature into the technical problem. Often the discussion was so inspiring that they ran the cycle again. They redefined the research question and repeated the search. In some cases a redefinition was needed to go more in detail of the identified natural organism or the like. In the final phase D both students decided on the main principle and generated a concept that incorporated the same. In the following the main questions and findings are presented according to the four phases.

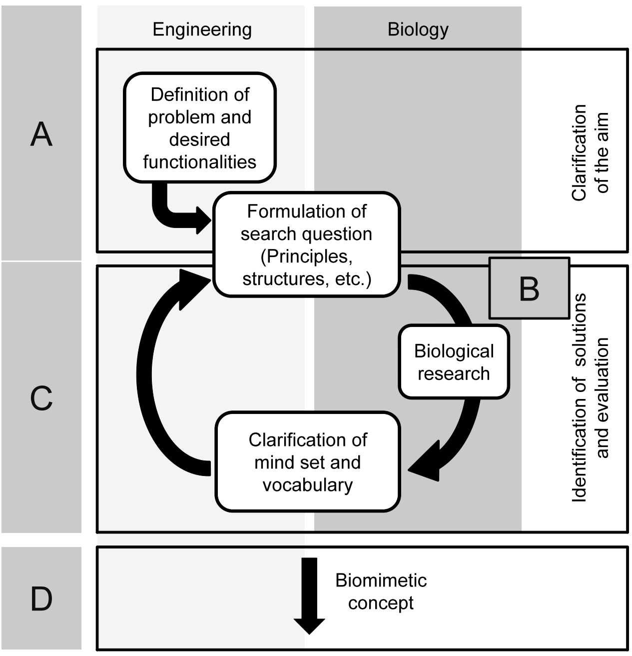


*Figure 6: Procedure of interdisciplinary team approach (adapted from Helten et al. 2011)*

As main requirements of a car bumper the engineering student defined the following ones: to protect the car from scratches and dents when bumping into another car, to absorb kinetic energy in a frontal crash and to improve the bumper as the first contact point with a pedestrian. Based on these requirements main functionalities were derived:

- Being stiff
- Being compressable
- Cushion the leg of a pedestrian

Finally they came up with the idea to use a liquid with a shear-thinning viscosity for energy absorbance as a principal solution. The fluid remains tenacious at low forces and get fluid at high forces.

The starting point of phase B was the generally formulated question how nature cares for shock absorbance. The biology student searched by the use of the following keywords for solutions in sources such as Ask Nature, libraries, internet and eol.org: biological shock absorbance/absorption, natural shock absorption, shock absorption of mammals/insects/birds/reptiles/amphibians, cats and human shock absorbance/absorption, molecular absorbance/absorption, shock absorbance in plants, and spinal disc/spinal column fluid. Related findings were the invertebral disc, ventricles of the brain, footpads bush-cricket, exoskeleton dragonfly, foot sole (humans), articular cartilage, and skeleton of cats, see table 1.

In phase C the interdisciplinary team looked for different kinds of viscosity in natural liquids. The liquor (the liquid between brain and skull) is of a similar viscosity as water, blood is a shear-thinning liquid, and sea-anemones use shear-thickening body liquids to enable extreme shape change. They furthermore seeked to understand the underlying structure of the intervertebral disc. The disc consists of a jelly core that absorbs the shock, surrounded by several layers of fibrocartilage. The final concept then had a similar structure.

***THE FOUND BIOLOGICAL ANALOGIES***

All together was 42 biological analogies found while working with the three approaches. The transfer checklist approach produced 20 phenomena of which 11 were considered to particular relevant after using the preselection procedure. The inspiration card approach resulted in 15 analogies and the interdisciplinary approach found 7 analogies. Nevertheless the sheer number of analogies is in general no indication for their quality and applicability. Table 1 lists all the found analogies.

## DISCUSSION

The basic research question for the present work was if the creative idea generation in design work could be stimulated using inspiration from nature. For all three approaches biological inspiration was found which favor a positive answer to this question. Remarkable is that the initial problem of car collision is taken from the automotive industry. The fact that so many ideas could be found emphasizes the usability of biomimetics in all industrial areas, not only the medical industry (see motivation). Impressively the students came up with rather different solution principles to the basic design problem, which is a desirable characteristic for good idea generation work. However, since a comparison study of idea generation without using biomimetic methods is missing, it is not possible to qualify the assumption that more or better result are possible using biomimetics.

The secondary research question refers to the similarities and differences between the three different approaches. In the following the main findings related to the overall approach and the solutions are presented.

*FINDINGS CONCERNING THE PROCEDURAL STEPS:*

**Procedural structure:** All three approaches present a top-down approach that starts with an explicit problem definition for the technical system and they all provide the possibility of a cyclic procedure incorporating several iterations. The interdisciplinary team approach includes micro-cycles during the discussion of possible solutions, whereas the transfer list approach shows a macro-cycle (after searching solutions if necessary). In contrast to the other two approaches, the transfer checklist approach is strongly formalized.

**Description of phenomenon:** The inspiration card approach focuses on a structured description of the biologic phenomena. In contrary, the interdisciplinary team approach shows up a less structured but due to involvement of a biologist a broader description of the phenomena.

| | |
|---|---|
| Transfer checklist team | 1.Musk ox, 2*.Duck, 3.Cat, 4.Flea, 5*.Woodpecker, 6*.Cassowary, 7.Dragonfly, 8.Birds' bones, 9*.Hedgehog, 10.Pied kingfisker, 11*.Pads cusion (mammals), 12*.Toucan beaks, 13.Flea, 14.Seeds from brazil nut trees, 15*.Stem, 16*.Horny skin, 17.Fiber alignment, 18*.Combs, 19*. Invertebral disk, 20*. Meniscus / collagen fibers |
| Inspiration card team | 1.Woodpecker pecking, 2.Fighting rams, 3.Falling cats, 4.Chicks that fall out of nest, 5.Egg shells, 6.Mussle shells, 7.Leg bones in landing birds, 8.Falling hedgehogs, 9.Spiderweb, 10.Nuchal ligament in grazing animals, 11.Butting dragonflies (exoskelleton), 12.Albumen – the fluid in bird eggs, 13.Mussle thread attachement to stones, 14.Swaying palm trees, 15.Wood cylinders |
| Interdisciplinary team | 1.Invertebral disk, 2.Ventricles with liquor, 3.Bush-cricket foodpads (partially fluid), 4.Dragonfly exoskeleton, 5.Foot sole, 6.Articular cartilage, 7.Skelleton of cats |

*Table 1. Overview of found biological analogies for the collision problem. A '*' indicate the phenomena is selected as more relevant for the desired properties.*

**Extent of information:** The transfer checklist supply only names of solutions and requires a further concretization by using literature. The two other approaches deliver first details already during the first search.

**Evaluation:** The transfer checklist incorporates a systematic evaluation of solutions. The interdisciplinary team approach includes an "intuitive" evaluation of solutions since the biologist has a deeper background knowledge about phenomena. Thus, a continuous pre-evaluation is done during the generation of ideas by the biologist. The Inspiration card approach does not include a formal evaluation of the found biological phenomena, but their value is indirectly measured since the designer have to formulate the functional principles when making the inspiration cards. If it is not possible to formulate a reasonable functional principle for an otherwise interesting biological phenomena, this is probably a good indication of less relevance.

***FINDINGS CONCERNING THE IDENTIFIED SOLUTIONS:***
All three approaches resulted in a number of useful biological analogies that represented principles for design mechanisms that solve the problem, and some of them were used to propose conceptual design solutions. The learning curve for the students was satisfactory. They all got sufficiently skilled to use the methods in about two weeks, which is of especially of interest for discussions about further industrial implementation. One group included a biology student. The collaboration between the two disciplines worked well. The students expressed their experience of a better understanding of the biological phenomena.

**Level of abstraction:** Comparing the solutions it can be seen that the transfer checklist approach provides solutions on the subsystems level (e.g. horny skin), whereas the description of the inspiration card approach contains the situation when the ability of the technical system is relevant (e.g. fighting rams, falling cats). The transfer checklist only names the biological phenomenon without explaining the use context (e.g. horny skin, stem). The interdisciplinary team approach delivers a description of the function owners (e.g. skeleton of cats).

**Congruence of solutions:** Interestingly, no identified solution can be assigned to all three approaches, but at least some solutions can be assigned to two of them. The solutions are complementary, and the solution space shows only a small overlap. Thus, the approaches can be accomplished complementary. The solutions of the card approach mostly show a zoologic background, whereas the interdisciplinary team approach shows more variation within the solution space – solutions come from human biology and zoology. The transfer list approach shows mainly human and zoology-oriented biological phenomena, still also providing botany-oriented (stem) and botany-associated (honeycombs) solutions.

## PERSPECTIVES

After the joined effort with students using biomimetic methods for generating design proposals for a specific problem we are more confident that biomimetics represent a promising way of improving systematic design work. Biomimetics can be approached on different knowledge levels and we find that valuable results can emerge even for the designer with only a modest knowledge of biology. In the present work 43 design principles were identified. However, large areas of the biology like cell biology, microbiology and biochemistry are difficult to access for the untrained and significant biomimetic search result from these areas require a certain level of knowledge typically found among biologists. A very positive finding from our work therefore was the fruitful collaboration between the engineering and the biology student in the interdisciplinary team. Beforehand we were afraid that biologists in a collaborative biomimetic design team only would see themselves as knowledge providers and therefore only have limited interest. The biology student emphasized that the collaboration increases the collaboration competences that would improve the student´s value on the labor market and give access to a broader variety of jobs.

Biomimetic design faces at least five difficulties or challenges that require increased research focus namely 1) problem delimitation, 2) biology search, 3) understanding biology phenomena, 4) formulate design principles and 5) communication of the biomimetic findings. The first and fourth difficulty are broader design challenges found in most design work and are addressed by the existing design research. To overcome the second and third difficulty biology/engineering collaboration and improved knowledge access is required. Improved collaboration is probably best approached at the education level where the different competences are brought together in mutual courses and projects. The improved knowledge access can be addressed through new types of dedicated knowledge sources or through more intelligent interfaces to the huge existing body of biology literature, such as the transfer checklist approach described in this paper, the asknature website (Asknature 2011) and the biotriz approach (Vincent and Mann 2002) are examples of the former. The inspiration cards described for one of biomimetic approaches in this paper represent one way of overcoming the communication difficulty.

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