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AN APPROACH TO SUPPORT SEARCHING FOR BIOMIMETIC SOLUTIONS BASED ON SYSTEM CHARACTERISTICS AND ITS ENVIRONMENTAL INTERACTIONS

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1. Introduction

Biology recovers promising solutions for all different kinds of challenges. Engineers have used biological examples to solve engineering problems since Leonardo da Vinci but in the last decades biology was increasingly recognized as a source of inspiration for technical developments. To successfully implement biological solutions in technical applications, biological knowledge has to be integrated in the engineering product development process. However, this is not trivial as biologists and engineers use different terminologies to describe their work. An effort has already been made to overcome the barrier of language on different levels of the development process. On the level of finding suitable biological analogies, databases have been set up that make biological knowledge available and usable for engineering. Furthermore, approaches have been proposed that use natural language analysis to bridge the linguistic gap between the two disciplines.

As detecting extraordinary natural solutions is crucial for creating innovative biomimetic designs, this paper focuses on improving the search and therefore the search results for biological analogs to a given technical problem by natural language analysis. Researchers that dealt with this topic so far used terms describing the functions of a technical system to overcome the above-mentioned terminological gap. Taking into consideration that a technical system is characterized by more than its functions, the question arises if it is beneficial to match technical and biological descriptions based on a system's design characteristics or interacting conditions with its environment. Especially the conditions a system interacts with seem to be promising because of two reasons. Firstly, interacting conditions can be formulated more globally as they are no direct part of the system of interest. Secondly, biological systems are always optimized to their living environment and looking at a system's interacting conditions can bring up biological solutions that perfectly match a technical system's requirements. Using aspects of technical systems aside from functions for matching can be particularly interesting for systems where structural aspects come to the fore.

Out of the motivation to provide additional assistance in mapping biological to technical documents and therefore to aid searching for biological analogs to technical questions a first attempt is made to perform natural language analysis based on system characteristics and its interacting conditions with its environment. In the following sections a literature survey on related research is given. Based on this survey further research questions are brought up and the approach to address these questions is introduced, illustrated with an example and discussed. In the end an outlook on future research activities is given.

2. Related research

There has been a lot of research on the issue of aiding engineers in finding and using biological solutions for technical problems. Within the design process an aid can either be provided on the search level or the level of transfer. This survey focuses on literature dealing with the search level that is the step of finding biological phenomena suiting a technical problem.
There are different approaches supporting the designer in finding promising biological analogs.

2.1 Research on biomimetic databases

Ask Nature [http://www.asknature.org] provides a search database containing biological phenomena and biomimetic products. It is based on a biomimicry taxonomy which is organized by design and engineering functions. The user has the opportunity to either visit webpages where biological strategies are exemplarily listed, find analogs to certain biological strategies, browse in categories (forum discussions, people, groups, products, strategies) or do a key word search. Search results contain descriptions of the biological phenomena and corresponding products, application ideas and references.
The idea generation software *IDEA-INSPIRE* developed by Chakrabarti [2005] is a database containing pairs of technical and biological systems represented by the SAPPhIRE model of causality. A search of analogs can be performed either directly by describing the problem in terms of the constructs of the SAPPhIRE model (verb-noun-adjective set) or by browsing the database for inspiration.
A computer-aided catalog providing biomimetic effects hierarchically organized by technical and biological solution categories (e.g. evolution and optimization or materials) and their corresponding principles (e.g. adaptive growth or fiber material, respectively) is suggested by Löffler [2009]. For each principle several biological phenomena are stored and linked by cross references. A key word search leads to the description of the phenomenon and associated references or links.
Two biomimetic knowledge bases that are not computer-aided are provided by the following authors: Hill [1997] developed a biomimetic design catalogue based on five elementary technical functions and three flow types which result in 15 classes according to which 200 biological principles are filed; Gramann [2004] proposes a list of biological assoziations to technical functions.
A disadvantage of databases is that the stored data has to be fed in manually what causes the fact that it has to be expanded or adjusted regularly to keep it up-to-date. This is in particular true for biological data as there are constantly new findings that disprove former results. Feeding, expanding and adjusting a large biomimetic database is time-consuming. The contained data as well as its design in the form of inherent classifications or links tends to be subjective as it is often based on a personal interpretation of the original biological or technical knowledge sources.

2.2 Research on natural language analysis

Stroble [2009] suggests an engineering-to-biology-thesaurus to link engineering and biological terminologies. The thesaurus includes flow type biologically connotative terms collected through functional word searches (not considering variations of the stem function word) of a biological textbook. Searching is described as an organized verb (Functional Basis functions)-noun (biologically connotative terms) search. The mapped terms of the two disciplines are placed into pre-determined classes according to the Functional Basis structure. The latter is stated to sharpen search results when searching for biological inspiration in a natural-language corpus.
Cheong [2008] translates terms of the Functional Basis into biologically meaningful keywords that enable designers to explore all the biological knowledge available in natural language format. The translation is based on a method proposed by Chiu [2007]. They start with a key verb describing the desired function and its synonyms, hypernyms and troponyms and use this to screen an introductory university-level biological textbook. Matching terms are filtered and bridge verbs are identified based on linking nouns that modify either the key verb or the biological verb. The difference between the approaches of Cheong [2008] and Chiu [2007] is that instead of searching by the key verbs' synonyms, hypernyms and troponyms in the work of Cheong [2008] the key verbs are grouped into classes. In case the original key verb does not produce a match, functional key verbs of the same class

can be used for a search. Cheong [2008] illustrates a Functional Basis reconciled function set with corresponding biologically meaningful keywords.
Nagel [2010] proposes an engineering-to-biology thesaurus that integrates the former two approaches.
Providing engineering-to-biology translation tools is advantageous compared to providing biomimetic databases because searching can take place in any biological knowledge source written in natural language format that is available. However, all of the above-mentioned approaches used functions as basis for matching technical terms to biological terms. In case of the thesauri as well as the biologically meaningful keywords suggested by Cheong [2008] relevant biological terms were identified using biological textbooks as a biological source of knowledge.

3. Research questions

Taking previous biomimetic research on natural language analysis into account four questions arise regarding a term-based support for exploring the biomimetic solution space.

1. *Is it beneficial to do an engineering-to-biology term matching based not only on functional terms but additionally on terms describing other aspects of technical and biological systems like its design characteristics or its interacting conditions with its environment?*
2. *Is it beneficial to do an engineering-to-biology term matching based not only on the search term as it is and its synonyms, hypernyms and troponyms but additionally on building the search terms' corresponding nouns, verbs or adjectives (e.g. absorber, absorption, absorb, absorbent, absorbing, absorptive) or its positive and negative forms (e.g. bending, unbending)?*
3. *Is it necessary to provide biologically relevant terms that bridge the gap between engineering and biological terminologies or is it sufficient to do a biomimetic search based on different categories of technical and biological terms and their variations?*
4. *Is it beneficial to do an engineering-to-biology term matching using biological or medical papers as a biological text source?*

Mapping biological papers to technical documents was also proposed by Vandevenne [2011]. In the approach presented here biological or medical papers are suggested due to the following reasons. Inspiration from papers is desired because they often deal with very specific details of biological systems that can bring up extraordinary biological analogs for technical questions. Beyond that, biological or medical papers represent the ongoing research. Using the latest of them reduces the possibility of wasting time trying to transfer outdated biological system descriptions to technical applications. Cheong [2008] also suggests using further biological documents for a keyword search in addition to or as substitution for the textbook they used as initial biological corpus for defining biologically meaningful keywords. As there are possibly slightly different terms used in biological textbooks and scientific papers it can be convenient to directly do the key term search in the latter.
A first attempt to answer the remaining first three questions is made by exemplarily doing natural language analysis on technical as well as biological documents dealing with safety helmets and shock absorbance, respectively. The underlying approach is described in the following section.

4. Approach

To address the aforementioned open research questions, biological or medical paper abstracts and corresponding technical descriptions or patents for 15 possible biomimetic pairs (e.g. safety helmets and equine hoof wall or technical grippers and elephant trunk) were annotated using certain term categories.
In this work the term annotation is used for extracting the documents' essential and relevant terms and clustering them into certain categories. The categories are defined partly on the basis of Gaag [2010], partly on the basis of the insights gained during the above-mentioned annotation.
Resulting annotation categories are:

- *function owner* (carries out the considered function of the particular system)
- *function owner characteristics* (characteristics of a particular system's function owner)

- *function* (functional verb that together with an object constitutes a function of the particular system)
- *interacting conditions* (environmental interactions with the particular system)

Documents for the annotation shall not be taken out of a biomimetic background because in this case the terminologies of the two disciplines engineering design and biology might already been mixed and no representative conclusions can be drawn from the findings.

After the annotation, categorized technical and biological terms are compared and matched within one category and across categories. For matching biological and technical terms the terms' synonyms are built using WordNet Search – 3.1 online. WordNet is a lexical database of English nouns, verbs, adjectives and adverbs which are related by cognitive synonymy [http://wordnetweb.princeton.edu/perl/webwn]. Matching is also based on building the terms' corresponding nouns, verbs or adjectives or the terms' positive and negative forms (+ & - in figure 1). Thus, two terms are considered a matching pair in case they are either the same from the outset or after building synonyms, building their corresponding nouns, verbs and adjectives or building their positive and negative forms.

This approach (figure 1) focuses on using the categories of *function owner characteristics* and *interacting conditions* as a starting point for matching engineers' and biologists' terminologies for the following reasons. For biomimetic pairs like the elephant trunk and technical grippers or the jump of a kangaroo and technical jumping devices that have the functions of gripping or jumping in focus there are a lot of functions present in the annotations of the technical as well as the biological documents. In contrast, for the equine hoof wall and technical devices for shock absorption such as safety helmets only two functions and therefore functional verbs are present in the considered biological abstract. The same was observed for spider silk and highly elastic and tear resistant materials. It is assumed that for systems where structural aspects come to the fore a term matching based on categories other than that of *function* can be beneficial. The *function owner* itself is often described in discipline specific terms and therefore not used as a category to start the match from.

The approach can be used by both engineers and biologists. Engineers can use it to search for biological analogs, biologists to search for possible technical applications suiting their phenomenon of interest. The advantage in usage is that the problem has not to be modelled in a certain way. Thus the user does not have to spend time on becoming accquainted with certain constructs before starting a search as it is the case when using models like SAPPhIRE for example.

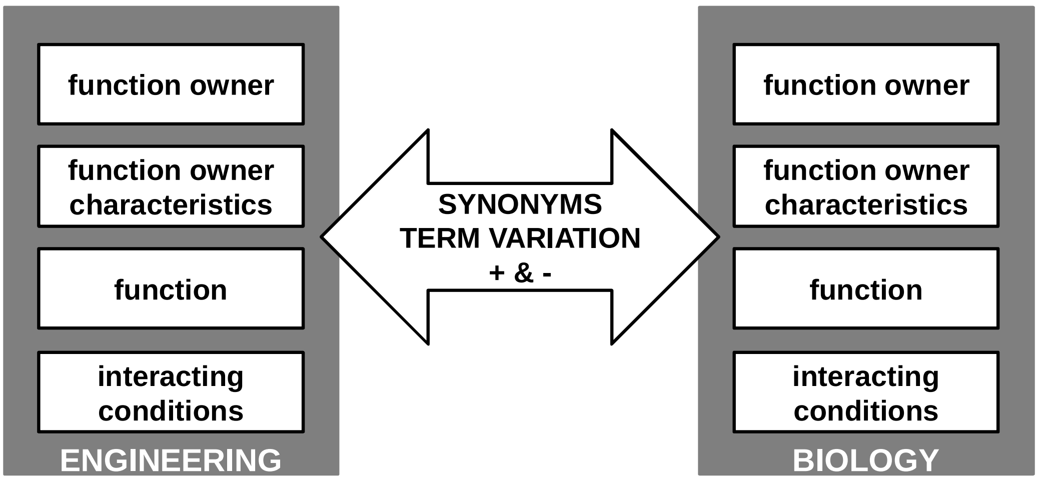

Figure 1. Model of the suggested approach

In the next section the approach shown in figure 1. is applied to the example of safety helmets and shock absorbance coming from an engineer's perspective.

5. Applying the approach to the example of safety helmets and shock absorbance

Three different types of technical documents describing safety helmets were annotated – a product description of a bicycle helmet, a Wikipedia article about motorcycle helmets and a patent for a safety hat. This was done to get a variety of technical terms available for the engineering-to-biology matching.

Table 1. Annotation of the considered technical documents concerning safety helmets

	product description – bicycle helmet [http://www.coneheadhelmets.com.au]	*Wikipedia – motorcycle helmet* [http://en.wikipedia.org/wiki/Motorcycle_helmet]	*patent – safety hat* [http://ip.com/patent/US2585937]
function owner	Cone-head liner cone shaped structures foam/ helmet liner crumple zone	motorcycle helmet headgear	safety hat headgear linings plastic material
function owner character-istics	shock absorbing	protective	rigid protective shock cushioning
function	dissipate impact forces reduce deceleration of head protect body parts/ goods	reduce risk of head injury/ death protect rider's head prevent head injury save rider's life	cushion head protect head absorb/ distribute force of impact
interacting conditions	impact impact forces	impact	falling objects shocks blows collision with objects

In the following, the terms annotated for the three different types of safety helmet descriptions are merged and compared to the annotations for four biological paper abstracts concerning shock absorbing phenomena – the equine hoof wall, hedgehog spines, articular cartilage and the heel pad.

Table 2. Results of the annotation of the considered technical documents concerning safety helmets and biological abstracts concerning shock absorption

	safety helmets/ hats	*paper abstract – equine hoof wall*	*paper abstract – hedgehog spines*	*paper abstract – articular cartilage*	*paper abstract – heel pad*
function owner	cone shaped structures foam/ helmet liner crumple zone headgear linings plastic material	hoof wall horn arrangement morphology tissue wall material struts tubule	spines shock absorber	articular cartilage water electrolytes matrix collagen proteoglycan fluid flow	heel pad tissue shock absorber
function owner characteristi cs	shock absorbing protective rigid shock cushioning	nonhomo-geneous mechanically anisotropic rigid strength compressive strength mechanical properties dependent on water content	short	solid viscoelastic deformational responses load-bearing capacity	shock absorbing load carrying ability stiffness variability pressure distribution shock reduction shock absorption load deflection

function	dissipate impact forces reduce deceleration of head/ risk of head injury/ death protect body parts/ goods/ rider's head/ head prevent head injury save rider's life cushion head absorb force of impact distribute force of impact	protect tissue store energy	bend delay onset absorb mechanical energy		
interacting conditions	impact impact forces falling objects shocks blows collision with objects	weightbearing tensile stress vertical compression	loaded axially local buckling load impact energy animal falls from height	loading conditions	gait plantar pressure

5.1 Findings for the category of *function*

For the category of *function* it is remarkable that for two of the four biological phenomena – namely articular cartilage and heel pad – there are no functional verbs listed at all in the abstracts. For the abstracts concerning the equine hoof wall and hedgehog spines in each case one functional verb can be easily matched with two of the technical functional verbs without using synonyms or term variations. The latter does not lead to additional matches. The biologically meaningful keywords suggested by Cheong [2008] corresponding to the functional verbs found in the descriptions of safety helmets do not bring additional matches as well.

5.2 Findings for the category of *function owner characteristics*

Figure 2 illustrates the biological term matches for the technical terms describing safety helmets in the category of *function owner characteristics*. Technical terms are grouped on the upper left side, biological terms of the particular phenomena are grouped within the clouds.

For the abstracts concerning the equine hoof wall and the heel pad matching terms can be found using the original technical terms characterizing safety helmets. No synonyms are necessary to do a matching. However, using the technical terms' synonyms in combination with building its corresponding nouns, verbs or adjectives results in an additional matching pair of terms in case of the hoof wall ("stiff" as a synonym of "rigid" was transformed into the noun "stiffness"). Turning the synonym "unbending" for the technical adjective "rigid" into its positive form "bending" and then building the verb "bend", leads to a match with one of the three functional verbs contained in the abstract describing hedgehog spines. This is an example for a match across categories starting from the category of *function owner characteristics* and resulting in the category of *function*.

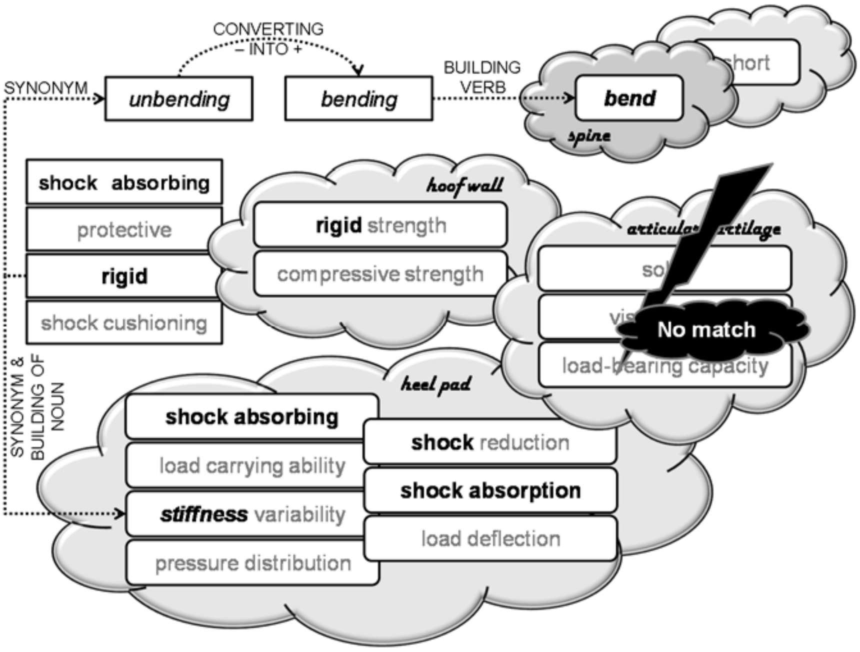

Figure 2. Engineering-to-biology term matching in the category of *function owner characteristics*

5.3 Findings for the category of *interacting conditions*

In the category of *interacting conditions* the biological term matches for the technical terms describing safety helmets are depicted in figure 3. As in figure 2 technical terms are grouped on the upper left side, biological terms of the particular phenomena are grouped within the clouds.

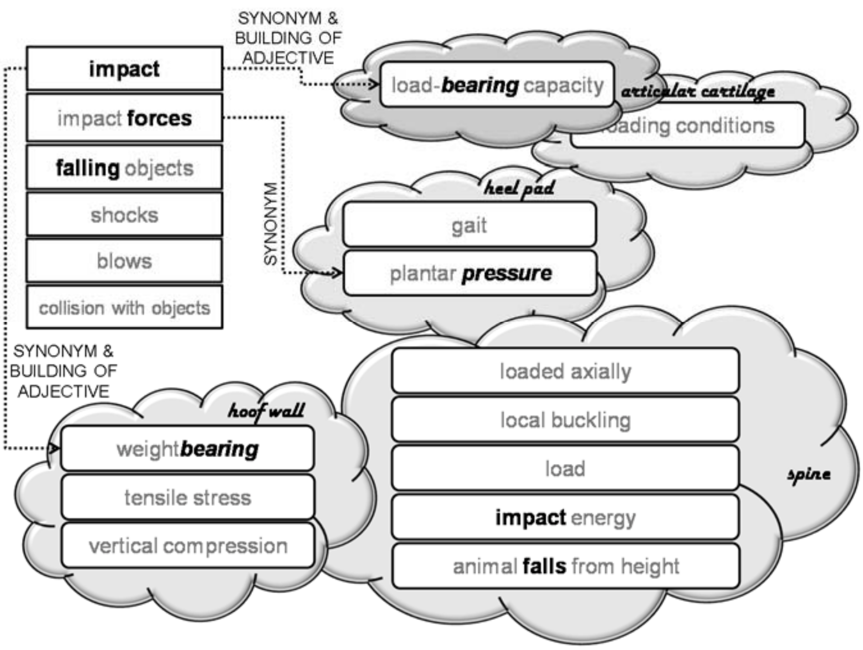

Figure 3. Engineering-to-biology term matching in the category of *interacting conditions*

Biological terms that could be matched directly to the technical terms are contained in the abstract describing the hedgehog spines. For matching biological terms contained in the abstracts concerning the equine hoof wall, the heel pad and the articular cartilage synonyms and variations of the technical terms have to be performed. Matching biological terms can be found in the abstracts describing the hoof wall and the articular cartilage by transforming the synonymous verb “bear” of the technical term “impact” into the adjective “bearing”. The technical term “force” delivers the synonym “pressure” that is also contained in the biological abstract about the heel pad. Thus, using the suggested approach, in the category of *interacting conditions* matching terms exist in all of the four biological or medical paper abstracts considered.

6. Discussion

One example of natural language analysis based on this work's approach it is not sufficient to draw universal conclusions from its results. However, the results shown above as well as the observations made during carrying out the analysis are a first justification for answering the three research questions raised in section 3 that are still open. The open questions and corresponding answers are given in the following.

Is it beneficial to do an engineering-to-biology term matching based not only on functional terms but additionally on terms describing other aspects of technical and biological systems like its design characteristics or its interacting conditions with its environment?

All examined biological descriptions dealing with shock absorbance focus on the systems' structural characteristics or their interactions with their environments. Therefore, it is supposed that, for kinds of biological documents where the fulfilling of the functions of the particular systems is not in focus but implicated in either the descriptions of their characteristics or their environmental interactions, the matching of technical terms – apart from functional verbs – to biological terms is beneficial. This can be especially true for biological phenomena that can provide inspiration for materials or structures like spider silk or honeycombs.

Is it beneficial to do an engineering-to-biology term matching based not only on the search term as it is and its synonyms, hypernyms and troponyms but additionally on building the search terms' corresponding nouns, verbs or adjectives or its positive and negative forming?

Matching in case of the example of safety helmets and shock absorbance was carried out using synonyms and term variations in the form of building corresponding nouns verbs or adjectives or the terms' positive and negative forms. Within the category of *interacting conditions* all technical terms can be matched with terms contained in the considered biological abstracts, however, not without building term variations. Adding these variations to the original technical terms for matching, results in additional matches for all considered categories. Matching with the help of term variations is therefore thought to be beneficial – at least considering this work's example. The technical terms' hypernyms and troponyms are not used for matching in order to keep the search and matching terms manageable with regards to a possible future practical implementation of this work's approach. The filtering of the synonyms taken for matching is left to the user. There are useless synonyms like – in this case – "military unit/ force/ group" for the term "force".

Is it necessary to provide biologically relevant terms that bridge the gap between engineering and biological terminologies or is it sufficient to do a biomimetic search based on different categories of technical and biological terms and their variations?

Categorizing the terms used in technical system descriptions can be helpful for searching for biological inspiration. Instead of using biologically meaningful keywords [Cheong 2008] or engineering-to-biology thesauri [Stroble 2009], [Nagel 2010] it can be beneficial to firstly structure a document, secondly decide on the category that seems most promising based upon the topic the document deals with and thirdly start searching using the terms listed in the chosen category together with their variations. If enough matches are achieved with this work's approach also for further biomimetic pairs remains to be proven.

Working with this approach in combination with existing biomimetic databases like *Ask Nature* [http://www.asknature.org] can also be beneficial. The referenced papers listed within this database's search results provide an indication for experts on exactly the topic of interest. Pointing out potential cooperation partners is another advantage of using papers as an initial biological corpus.

7. Conclusion and future work

The approach suggested in this work aims at aiding engineers in fully exhausting the inspiring potential of biology in order to come up with extraordinary solutions to technical problems. On the other hand biologists can search for technical applications for their phenomena of interest. The approach uses natural language analysis to facilitate the search for these biological solutions or technical applications. Searching is based on technical or biological terms divided into different categories. Focussed are the categories containing terms used for describing characteristics of a certain system and for the system's interactions with its environment. In this paper's example technical terms contained in these categories are taken and, if necessary, either their synonyms or term variations are built to match it to the annotated biological terms. The example shows that basing the matching not only on functional verbs can be beneficial for questions dealing more with a system's structure than its function. Another finding is that by choosing an appropriate category, new terms bridging the terminological gap between engineering and biology are not needed.

Future work will include the testing of the approach using further technical and biological documents dealing with different topics that focus on the considered systems' structural aspects. Furthermore the approach has to be tested from both the engineer's and the biologist's perspective. If the approach is still beneficial then there are different possibilities to implement it in – and therefore support – solution finding in biomimetic design processes. The approach could be implemented in a biomimetic software tool that, for example, was coupled to software tools that automatically built synonyms and the required term variations and was attached to search engines for either biological or technical documents. The user only had to select and enter the terms assigned to the chosen term category manually. The decision which category or categories to start from or use was also left to the user. To make the amount of documents matching the terms manageable, the documents could be sorted by their directness in respect of matching terms (direct match, match after one term variation, match after two term variations, etc.). Documents directly matching the inserted terms might contain more suitable solutions to the given problem. Another possibility was to cluster documents that cover the same topic. Thus the user was supported in finding different biological solutions by choosing documents out of different clusters instead of going through all the matched documents.

References

Chakrabarti, A., Sarkar, P., Leelavathamma, B., Nataraju, B. S.,"A functional representation for aiding biomimetic and artificial inspiration of new ideas", Journal of Artificial Intelligence for Engineering Design, Analysis and Manufacturing, Vol.19, Issue 2, 2005, pp 113-132.

Cheong, H., Stone, R. B., Shu, L. H., McAdams, D. A., "Translating terms of the functional basis into biologically meaningful keywords", Proceedings of IDETC/CIE, New York, 2008.

Chiu, I., Shu, L. H., "Biomimetic design through natural language analysis to facilitate cross-domain information retrieval", Journal of Artificial Intelligence for Engineering Design, Analysis and Manufacturing, Vol.21, 2007, pp 45-59.

Gaag, Andreas, „Entwicklung einer Ontologie zur funktionsorientierten Lösungssuche in der Produktentwicklung", Lehrstuhl für Produktentwicklung der Fakultät für Maschinenwesen der Technischen Universität München, Verlag Dr. Hut, München 2010.

Gramann, J., „Problemmodelle und Bionik als Methode", Lehrstuhl für Produktentwicklung der Fakultät für Maschinenwesen der Technischen Universität München, München, 2004.

Hill, B., „Innovationsquelle Natur", Shaker Verlag, Aachen, 1997.

Löffler, S., „Anwenden bionischer Konstruktionsprinzipe in der Produktentwicklung", Fakultät für Maschinenbau der Technischen Universität Carolo-Wilhelmina zu Braunschweig, Braunschweig, 2008.

Nagel, J. K. S., Stone, R. B., McAdams, D. A., "An engineering-to-biology thesaurus for engineering design", Proceedings of IDETC/CIE, Montreal, 2010.

Stroble, J. K., Stone, R. B., McAdams, D. A., Watkins, S. E., "An engineering-to-biology thesaurus to promote better collaboration, creativity and discovery", Proceedings of the 19th CIRP Design Conference – Competitive Design, Cranfield University, 2009, pp 355.

Vandevenne, D., Verhaegen, P.-A., Dewulf, S., Duflou, J. R., "A scalable approach for the integration of large knowledge repositories in the biologically-inspired design process", ICED, Technical University of Denmark, 2011.

Biological or medical literature used for the example

Cohen, N. P., Foster, R. J., Mow, V. C., "Composition and dynamics of articular cartilage: structure, function, and maintaining healthy state", The Journal of Orthopaedic and Sports Physical Therapy, 28(4), 1998, pp 203-215.

Leach, D. H., "The structure and function of the equine hoof wall", Department of Veterinary Anatomy of the University of Saskatchewan, Saskatchewan 1980.

Rome, K., "Mechanical properties of the heel pad: current theory and review of the literature", The Foot, Vol.8, Issue 4, 1998, pp 179-185.

Vincent, J. F. V., "Mechanical design of hedgehog spines and porcupine quills", Journal of Zoology, Vol.210, Issue 1, 1986, pp 55-75.

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