BIOscrabble
Extraction of Biological Analogies out of Large Text Sources

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1 STAGE OF THE RESEARCH

The aim of the research presented here is a support for solution search in bio-inspired design. More specifically, the engineer shall be supported in extracting biological analogies out of large text sources whereby the biological analogies must have the potential to solve given technical problems. To reach this aim, an approach has been developed by Kaiser (Kaiser, 2012) which in the first instance focuses on

- the large text source that shall be scanned and
- the search terms that shall be used to describe the technical problem.

As the proposed text source – biological research articles – is large and, therefore, the extraction of useful analogies is challenging, the approach proposed by Kaiser (Kaiser, 2012) needs further development. Research started on how to manage large amounts of information. In contrary to the research on existing support for bio-inspired design, research on managing large amounts of information is still in the early stages. Initial case studies have been conducted in order to test the applicability and practicability of the existing approach and to understand how to support information management in bio-inspired design.

2 RESEARCH PROBLEM

> *The voyage of discovery is not in seeking new landscapes but in having new eyes.*
>
> *Marcel Proust*

The question of how the huge amount of already recorded biological information can be discovered and used for developing innovative technical solutions has been driving engineers for centuries. In the recent decades, research activities in the field of bio-inspired design intensified. To effectively support the exploitation of existing biological solutions for designing technical products, two main questions can be addressed: 1) How can a promising biological solution be identified by an engineer who does not have a biological background? and 2) How can this engineer transfer a promising biological solution into a technical concept or product?

This research focuses on answering the first question. In literature, two approaches can be distinguished. On the one hand, databases have been established to provide the engineer with edited and often simplified biological knowledge (http://www.asknature.org/, (Chakrabarti, 2005); (Löffler, 2008); (Gramann, 2004); (Hill, 1997). On the other hand, researchers tried to find ways to support the engineer in effectively using biological knowledge that is available in text format (research on this area is discussed in detail in Sec. 5). In contrast to databases, the latter approaches do not face challenges such as the need of being initially filled and kept up-to-date or the risk of accessing subjectively misinterpreted biological data. Therefore, the authors decided on providing further support in this research area.

Searching biological analogies in biological literature is not trivial: a search term-based search in these sources can display an enormous amount of biological information. It is therefore challenging for an engineer to identify the right biological analogy for a given technical problem. This is especially true for searching in biological research articles. Nevertheless, this search source is very comprehensive and represents the current state of biological research and is hence worth further consideration.

3 OUTLINE OF OBJECTIVES

This paper illustrates an approach – called BIOscrabble – that aims at supporting solution search in bio-inspired design or, to be more precise, at supporting the search term-based extraction of

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relevant biological analogies out of large biological text sources. The objectives of this paper are:

- to present the approach BIOscrabble that
  - supports the engineer in performing search term-based searches in large biological text sources. The engineer is advised to choose search terms that describe the technical problem entirely and aptly.
  - proposes prospects for supporting the engineer in managing a large number of search results by using a graph-based representation of the search.
- to discuss the implications of the application of BIOscrabble for the search process and the organization of the search results.

4 STRUCTURE OF THIS PAPER

In Sec. 5 an overview on related research activities in the field of discovering biological analogies in text sources is given. Sec. 6 and 7 illustrate the BIOscrabble approach and the BIOscrabble software prototype. The application of BIOscrabble is discussed in Sec. 8. The discussion is based on findings from case studies in which BIOscrabble was applied to technical problems. The expected outcome of the BIOscrabble research project is illustrated in Sec. 9. The paper concludes with an outlook on future work in Sec. 10.

5 STATE OF THE ART

Research activities have been conducted that focus on the question of how to effectively discover biological information available in text format. In the following, an overview over research activities is given that address the issues of choosing text sources and search terms, overcoming linguistic differences between engineers and biologists and identifying relevant biological analogies.

5.1 Text Sources

Which text sources have been proposed for an effective discovery of biological information available in text format so far?

A natural language approach to biomimetic design has been developed at the University of Toronto. Keyword searches were performed and analysed in an introductory biological textbook to support an effective retrieval of biological information available in text format. The textbook was chosen as an initial text source, because 1) it is intelligible for a reader without a biological background and 2) it provides biological information ranging from molecular structures to ecosystems (Shu, 2010); (Cheong, 2012).

Biological textbooks were also used by Stroble et al. and Nagel et al. (Stroble, 2009); (Nagel, 2010) for compiling engineering-to-biology thesauri and by Nagel and Stone (Nagel, 2011) for testing a methodology for facilitating systematic biologically inspired design (including searching for biological analogies).

These textbook-based approaches can be applied to any other text source. However, advanced sources such as biological research articles are suggested for finding further details on selected biological analogies rather than for initial searching (Shu, 2010).

The World Wide Web was analysed as an initial source from which biological inspiration can be drawn by Vattam and Goel (Vattam, 2011). Searching the web for relevant biological analogies was found to be very costly in terms of time spent on searching and analysing (resource costs). The probability of spending time on analysing useless information or of ignoring useful information due to uncertainty was found to cause additional costs (opportunity costs). Using the web as an initial source for searching for biological analogies was also explored and supported by Vandevenne (Vandevenne, 2011; 2012b). The approaches are further described in Sec. 5.4.

The approaches described in Sec. 5.1 did not focus on using biological research articles as an initial search source for discovering biological information available in text format. As biological research articles are representing biological research most comprehensively, they are used as an initial search source in the approach proposed here.

5.2 Search Terms

What types of search terms have been proposed for an effective discovery of biological information available in text format so far?

To search biological texts for relevant biological analogies, at the University of Toronto, primarily verbs describing the desired technical function or effect were used as search terms (Shu, 2010); (Cheong, 2012). In one work the use of adjectives describing the desired technical qualities was illustrated (Ke, 2010). Nouns were found to indicate preconceived solutions and were therefore neglected

(Shu, 2004; 2010).

Functional technical terms or terms of the Functional Basis (widely accepted characterization of product functions in a verb-object (function-flow) format (Stone, 2000) serve as basis for the biological terms in the engineering-to-biology thesauri developed by Stroble et al. and Nagel et al., (Stroble, 2009); (Nagel, 2010). The engineering functional terms contained in the thesauri play a central role in searching for relevant analogies in the methodology proposed by Nagel and Stone (Nagel, 2011) which aims at facilitating systematic biologically inspired design.

For identifying biological analogies, functions or functional verbs of technical or biological systems are central in the work of Vandevenne (Vandevenne 2011).

It can be concluded that the approaches described in Sec. 5.2 mainly focus on system functions to discover biological information available in text format. In the approach proposed here, search terms describing system properties and environmental influences on systems are additionally focused on.

5.3 Terminology

What options have been revealed to bridge the gap between an engineer's and a biologist's terminology so far?

At the University of Toronto, two alternatives were revealed which can mitigate linguistic differences between engineers and biologists. First, it was found that the chance of identifying relevant biological analogies in biological text sources increases when the engineering functional search terms are expanded by term variations such as synonyms (Vakili, 2001); (Hacco, 2002). Second, a method for identifying biologically meaningful keywords was developed (Chiu, 2005; 2007). Textbook words collocated with the functional search terms initially used for searching were defined as biologically meaningful keywords dependent on their occurrences in further text sources. Biologically meaningful keywords were furthermore defined for the terms of the Functional Basis (Cheong, 2008).

To link engineers' and biologists' terminology and, therefore, sharpen search results when performing a key word search, engineering-to-biology thesauri have been developed by other research groups (Stroble, 2009); (Nagel, 2010).

Biologically meaningful keywords or keywords contained in the engineering-to-biology thesauri are only available for a portion of functional search terms. Therefore, in this work common term variations such as synonyms are used for varying search terms.

5.4 Identifying Biological Analogies

What decision guidance has been given for effectively identifying relevant biological analogies described in text format so far?

Researchers at the University of Toronto approached this question as follows: 1) Hacco and Shu detected characteristics of biological texts that contain irrelevant biological analogies (Hacco, 2002). When searching for biological analogies, these characteristics can form the basis for a systematic removal of irrelevant search results and, therefore, assist the engineer in identifying relevant analogies. 2) A characteristic of biological texts that can effectively be used as design stimuli is the explicit description of biological principles (Mak, 2004). A case study showed that the effort for selecting relevant biological systems is reduced when the principle has not to be abstracted from described behaviors or forms. 3) To further support the engineer in identifying relevant analogies, different methods for categorizing biological information have been developed based on semantic relations (Ke, 2009); (Cheong, 2012); (Son, 2012). Categorized biological information was found to assist the engineer in selecting analogies relevant to the design problem (Ke, 2009); (Cheong, 2012).

Further support for identifying relevant biological analogies was provided by Vandevenne (Vandevenne, 2011; 2012a; 2012b) in different ways: 1) To support the identification of relevant analogies, textual descriptions of biological systems that are detectable in the web were automatically characterized and mapped to technical problem descriptions (Vandevenne, 2011). 2) To support the structuring and, therefore, the selection of biological information available in text format, Vandevenne et al., introduced a method for classifying biological analogies into the Biomimicry Taxonomy of the Biomimicry Design Portal Ask Nature (http://www.asknature.org/, Vandevenne, 2012a). 3) For filtering out and preselecting biological information that is available in the web, a webcrawler was developed that continuously collects documents containing biological information that is relevant to biomimetics (Vandevenne, 2012b).

In the approaches described in Sec. 5.4, no assistance for identifying biological analogies

described in biological research articles was provided explicitly. Nevertheless, concepts such as the categorisation or clustering of biological information are used in the approach proposed here.

6 BIOscrabble – APPROACH

As with the approaches described, BIOscrabble supports the effective discovery of biological information available in text format. The main differences to the existing approaches described in Sec. 5 are: 1) the exclusive use of biological research articles as an initial search source, 2) the explicit inclusion of search terms that describe a desired technical system's properties and the environmental influences on this system and 3) the use of a graph-based representation of the search that has been carried out for assisting the engineer in identifying relevant biological analogies.

In the following, the BIOscrabble approach and a BIOscrabble software prototype are illustrated. BIOscrabble is a further development of the approach proposed by Kaiser (Kaiser, 2012). In the following a short overview over BIOscrabble is given. Further descriptions of the BIOscrabble steps and components as well as the reasons for their inclusions are given in Sec. 6.2 – 6.5.

6.1 Overview

For the effective discovery of biological information available in text format, the following steps are proposed in BIOscrabble (Fig. 1):

1) The user – here the engineer – describes the technical problem under consideration in terms of system functions, system properties and the environmental influences on it (definitions see below). The search terms for the following search process are taken from this description.
2) The search terms are varied, e.g. synonyms are built. WordNet (description see below) provides assistance here.
3) The database PubMed (description see below) is searched using the original and the varied search terms.
4) The PubMed search results, i.e. the biological research articles are clustered and displayed to the user in the form of structured graphs.

6.2 Text Sources

BIOscrabble supports using biological research articles as initial text sources when searching for biological analogies via search terms.

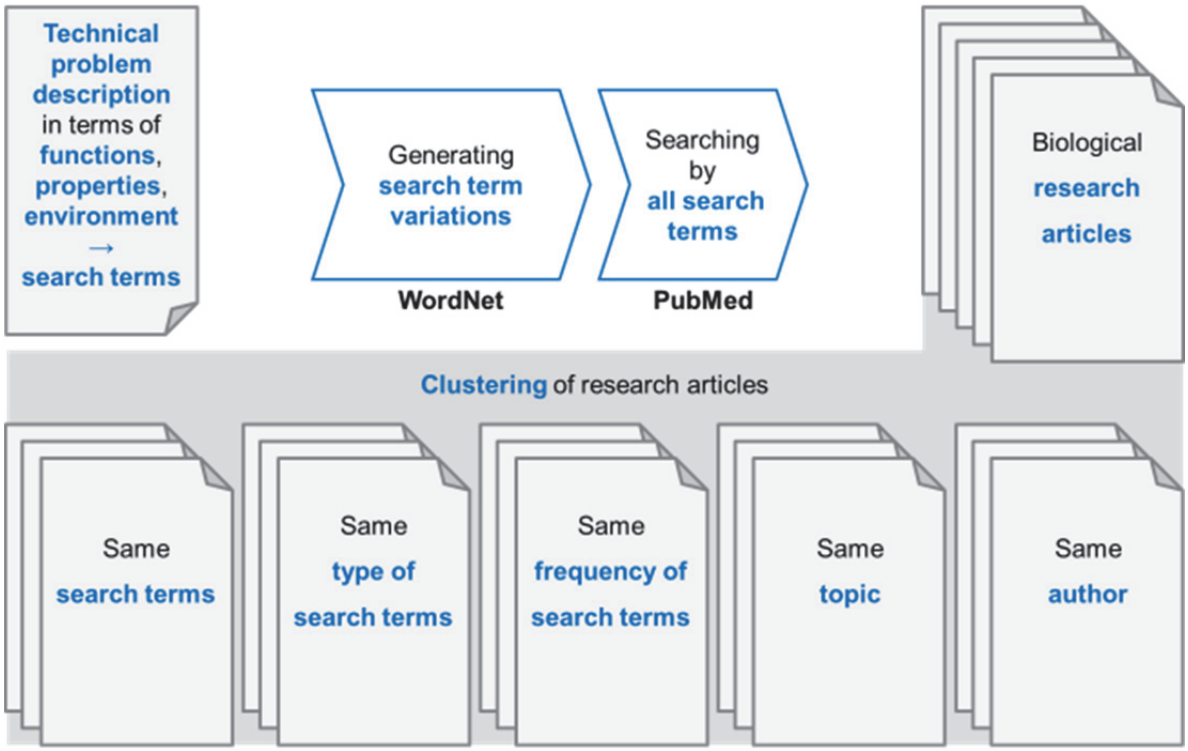

Figure 1: BIOscrabble search process.

In BIOscrabble, PubMed is used as a search source (http://www.ncbi.nlm.nih.gov/pubmed/). PubMed is a meta-database (i.e. a database of databases) that refers to more than 22 million citations for biomedical literature. Besides citations in the field of biomedicine, health and bioengineering, life sciences, behavioural sciences and chemical sciences are addressed. PubMed was developed and is maintained by the National Center for Biotechnology Information (NCBI). It can be freely used. PubMed can be searched by search terms. Search terms can be connected by Boolean operators such as AND or OR. Connecting search terms with AND results in citations that must contain all search terms connected. Connecting search terms with OR results in citations that must contain at least one of the search terms connected. PubMed provides different filters that can be set when performing a search. The BIOscrabble user is advised to set the filter "abstract available". This filter secures that at least an article's abstract is available in addition to its title. This is the minimum requirement for the identification of relevant search results.

Biological research articles were chosen as an initial search source, because this text source is very comprehensive and represents the current state of biological research. In biological textbooks, not all biological research findings are illustrated or illustrated in detail. This was stated in interviews with biologists that were conducted within a project aiming at the development of a communication platform for engineers and biologists.

6.3 Search Terms

BIOscrabble advises to search for biological analogies in biological research articles by search terms that describe a desired technical system's functions, properties or the environmental influences on this system. This search schema encourages the engineer to see the considered technical problem or system from different angles which can increase the diversity of the search terms. This, in turn, is supposed to enhance the probability of detecting relevant biological analogies.

6.3.1 Functions

Search terms describing technical functions are included in BIOscrabble because of two reasons: 1) Existing research dealing with the discovery of biological analogies in biological text sources showed that good results can be obtained by using functional search terms (Shu, 2010, Vandevenne, 2011, Cheong, 2012). 2) Functions play a key role in modelling technical systems (Stone, 2000, Pahl, 2007, Erden, 2008). Engineers are therefore trained in describing a technical system by its functions.

In this work, functions are defined according to Pahl et al., (2007).

6.3.2 Properties

BIOscrabble includes search terms describing technical system properties for the following reason: Compared with engineers, biologists do not focus on describing biological systems in terms of functions as the concept of function is not an issue during their academic training. Therefore, biological systems which are not primarily described functionally can be missed when searching with functional search terms only. In a pre-study carried out by the authors, spider silk, for example, was found to be described in terms of system properties rather than system functions.

Here, properties are defined according to Eder qnd Hosnedl (2008).

6.3.3 Environmental Influences

Natural systems are strongly aligned to the environmental influences they are exposed to as they evolve driven by their environment. Therefore, search terms that describe the environmental influences on a technical system are assumed to lead to relevant biological analogies. The above named pre-study confirmed this assumption. Consequently, environmental influences are included in BIOscrabble as a search term type.

In this work, the environment is defined according to Srinivasan and Chakrabarti (2009). Environmental influences are hence the influences of the environment on a technical system.

6.4 Terminology

To account for differences between an engineer's and a biologist's terminology, the BIOscrabble user is advised to vary the search terms (original search term) he or she picks. The following search term variations (varied search term), some of which are supported by WordNet (see below), are included in BIOscrabble: 1) synonyms of the search term, 2) nouns, verbs and adjectives derived from the search term and 3) antonyms of the search term. If the search term would be "purifying", 1) could be "cleansing", 2) would be "purification, purify and pure" and 3) would could be "adulterating".

Synonyms are included as they were found to increase the chances of getting relevant matches in case of searching a biological textbook for biological analogies via engineering functional search terms (Vakili, 2001); (Hacco, 2002). The authors assume that this is also true for searching biological research articles with search terms describing technical functions, properties or environmental influences. Deriving nouns, verbs and adjectives from a search term has the potential to broaden the solution space without leading to results that vary from the topic. BIOscrabble uses WordNet for automating some of the above mentioned search term variations (http://wordnet.princeton.edu/). WordNet is a lexical database of English nouns, verbs, adjectives and adverbs which are related by cognitive synonymy. WordNet was also used at the University of Toronto (Hacco, 2002); (Chiu, 2007); (Ke, 2010); (Cheong, 2012) for varying the terms used for searching biological text sources for analogies.

6.5 Identifying Biological Analogies

BIOscrabble proposes to use graph-based representations of search processes in bio-inspired design to support the engineer in identifying biological analogies that are hidden in large text sources.

Graphs are abstract structures which represent objects and their relations. Objects are represented as nodes, relations are represented as edges. Here, typed attributed graphs are used that contain three kinds of node types and two kinds of edge types: the node types are 1) original search term, 2) varied search term and 3) research article, the edge types are 1) edges linking search terms to their variations and 2) edges linking search terms (original or varied) to the research articles in which they are contained.

Graphs showing the relations between the original search terms and the varied search terms, between the search terms (original and varied) and the corresponding research articles or between different research articles can support the identification of biological analogies in different ways. The engineer can work with graphs that

- cluster research articles in which the same search terms are contained
- cluster research articles in which the same types of search terms (function, property, environmental influence; original term, varied term) are contained
- cluster research articles in which the same or different search terms are contained with a certain frequency
- cluster research articles which are cited by each other
- cluster research articles which are written by the same first authors

These clusters can be supportive. Research article samples can be taken within each cluster and examined for relevant biological analogies. If the samples within one cluster are promising the cluster can be examined further. The large amount of research articles a PubMed search generally produces therefore is divided into manageable "packages". The benefit of categorizing or clustering biological information is shown in (Ke, 2009, Vandevenne, 2011, 2012a, Cheong, 2012).

7 BIOscrabble – SOFTWARE PROTOTYPE

From a certain amount of search results (> 50) onwards it is impracticable to generate these graph views manually. Therefore, the BIOscrabble search process including the generation of the search graph has been automated in a software prototype.

7.1 Front End

By default the user is asked to enter search terms describing system functions, system properties and environmental influences on the desired system. These different types of search terms can be connected via check marks in order to search for research articles that contain more than one type of search terms. Check marks correspond to the Boolean operator AND. Empty check boxes correspond to the Boolean operator OR. In this case all research articles are searched in which at least one type of search terms is contained. To exclude research articles containing particular terms, unwanted terms can be added.

The user has the possibility to exclusively search for review articles by setting the filter "Review Articles". Research articles which are freely available in the full text version can be searched for by setting the filter "Fulltext Available Articles".

As a result of the search process, a table is displayed. This table contains the titles and the first authors of the resulting research articles as well as their rank and their rating. The rank increases with the value of the rating. Both are dependent on the

search terms' frequency in each search result (see 7.2).

The search results can be sorted by their rank, their title, their terms, their first authors and their rating.

For every search process the corresponding search graph can be viewed and saved as well as exported as a .graphml file. In the graph, information about the node and edge types as well as information about the rank and rating of the resulting research articles is contained.

Fig. 2 shows the graphical user interface (GUI) of BIOscrabble.

7.2 Back End

After the search process has been started by the user, the search terms which have been entered are varied. For the variation of the search terms WordNet Search – 3.1 is used online. Each search term is connected to its variations by the Boolean operator OR.

Depending on the user input, the different types of search terms are connected by either the Boolean operator AND or OR. The resulting search phrase is used to search PubMed for biological research articles. The PubMed filter "abstract available" is set automatically for the reasons mentioned in Sec. 6.2.

The search terms (original and varied) that are contained in an article's title or abstract are counted.

For the generation of the search graph the following information is extracted from the search process: 1) which term is the origin or the variation of which other term, 2) which term is contained in which article and 3) how frequently is a term contained in one article (necessary for representing the article's rank and rating).

With the current software prototype it is possible to distinguish articles according to the frequency of the search terms that are contained. As explained in Sec. 7.1 the frequency of the search terms is reflected in the rating and rank of the articles. The rating is calculated as shown in equation 1:

$$rating = 2 * a + b \quad (1)$$

In equation 1, a is the number of different search terms contained in a research article and b is the total number of search terms found in the article.

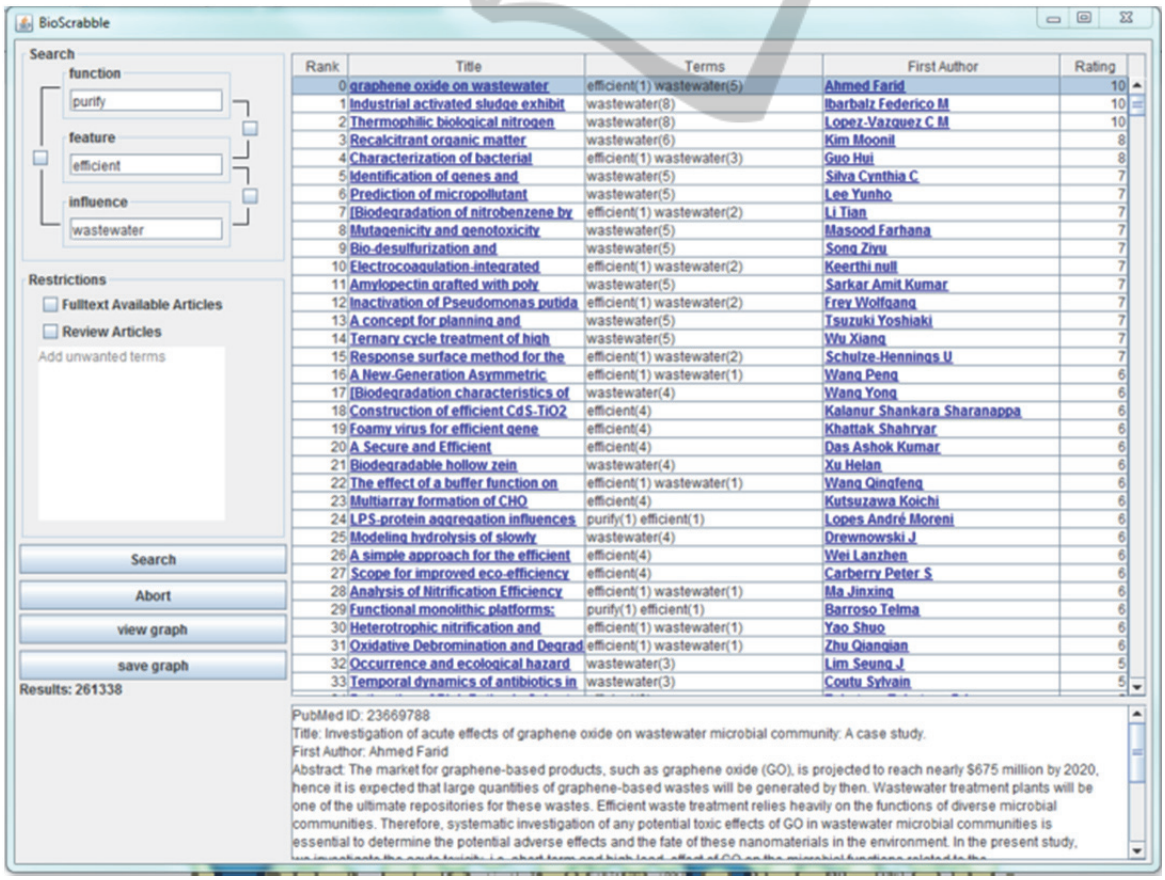

Figure 2: Screenshot of BIOscrabble GUI.

Equation 1 reflects one of the observations made during the application of the BIOscrabble approach to different technical problems in case studies with students of mechanical engineering (see 8.3).

Fig. 3 shows two graphs of an exemplary search. The left graph shows the raw representation of the relations between the search terms and the research articles they are contained in. The right graph shows the same relations, but the rank of the articles is reflected in the size of the nodes representing them, i.e. articles with a higher frequency of search terms are represented in bigger nodes.

The implementation of other graph-based representations (see above) is in the concept stage.

8 DISCUSSION

In the following, the approach of BIOscrabble is discussed based on the documentation of case studies in which BIOscrabble was applied to different technical problems. In these case studies, students of mechanical engineering were asked to solve a given technical problem applying to the search process proposed by BIOscrabble and to document their results. They did not use the software prototype and, therefore, were not supported in the identification of biological analogies. For brevity, the technical problems are not discussed in detail here.

The proposed text source, the proposed types of search terms including the proposed variations and the proposed support for the identification of biological analogies are discussed separately.

8.1 Text Sources

Biological research articles which are available via PubMed proved to be a text source which can provide useful biological information for the developments of bio-inspired products. Besides articles about biological systems, articles that describe bio-inspired or other technical products which are used in a biological context were found to be useful for the solving of the considered technical problems.

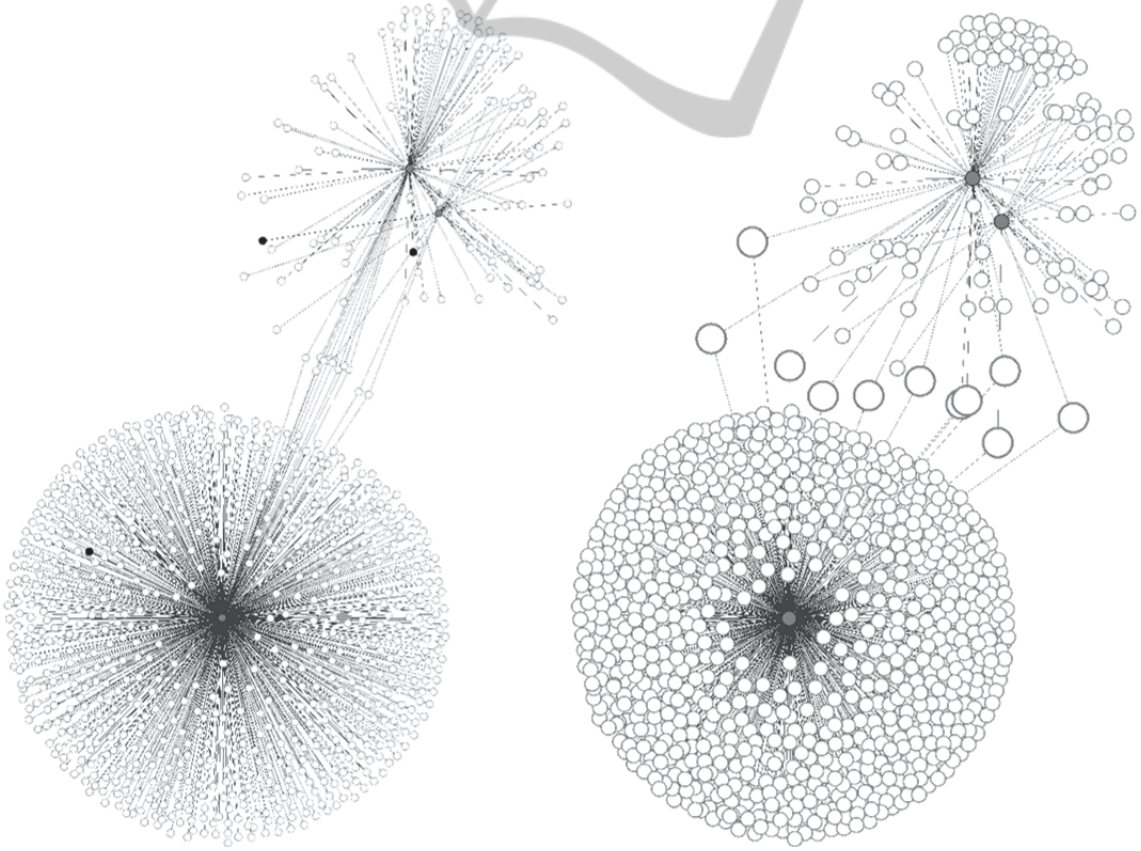

Figure 3: Exemplary graphs; left: raw representation, right: edited representation; black: node type original search term, grey: node type varied search term, white: node type research article.

Therefore, PubMed can be viewed as a search source that is not only useful for the development of bio-inspired products, but can also serve as a tool for finding analogies in general.

For most PubMed searches an impracticable amount of research articles is displayed. Without additional support it is very time-consuming to identify articles that contain useful biological information. To make a high amount of search results manageable within a reasonable time, graphs, as described above, can be supportive.

In conclusion, PubMed is a promising text source for finding biological or other analogies for solving technical problems. However, the engineer has to be supported in exploring the huge amount of search results. Furthermore, biological research articles are more appropriate for getting inspiration of what biological systems exist than for understanding the basic principles behind them. For engineers, many of them are hard to understand.

8.2 Search Terms

The case studies show that depending on the technical problem different types of search terms led to useful biological analogies.

In most cases, the best results were obtained by searching with AND combinations of search terms of the types function, property and environmental influence. Nevertheless, there were technical problems that were solved using biological systems contained in articles that were found by only one type of search term. Examples are the design of an adaptive surface with variable heat conductivity, a self-sharpening knife or a tension-reducing mechanism for stuffed pieces of luggage. In case of the adaptive surface, functional search terms were most beneficial. For the knife and the tension-reducing mechanism, search terms of the type system property and environmental influence led to the best analogies.

Search term variations in all cases led to additional relevant biological analogies.

It is concluded that the types of search terms that are proposed as well as the search term variations are beneficial for the discovery of biological analogies in large text sources. Whether the benefit of certain search term types or term variations depends on the kind of technical problem remains to be proven.

8.3 Identifying Biological Analogies

The graph-based representations proposed in Sec. 6.5 were not available for the participants of the case studies as they did not use the BIOscrabble software prototype. Nevertheless, conclusions concerning a support for identifying biological analogies can be drawn from the relations between the search terms that were used for searching PubMed and those research articles that contain relevant biological analogies.

For the development of a device for purifying drinking water, the relevance of the research articles correlated with the frequency of search terms that are contained. Additionally, a slight correlation between the relevance of an article and the frequency of different types of search terms was observed. These findings are realized in the paper rating and ranking mechanism that is implemented in the current BIOscrabble software prototype (see Sec. 7).

For the other design case studies, this observation did not prove true. In case of the self-sharpening knife the most relevant research articles contained only one single search term. Although, all articles that were relevant for the development of a self-sharpening knife dealt with only two topics, namely “teeth” and “claws”. Therefore, a graph that shows clusters of research articles that are cited by each other or are written by the same first author – and thus are supposed to deal with a similar topic – is proposed.

Whether the other graphs that are proposed in Sec. 6.5 can be beneficial remains to be proven.

9 EXPECTED OUTCOME

The expected outcome of this research project is to provide a functional software tool for supporting solution search in bio-inspired design. The expected partial outcomes are the following:

- BIOscrabble will provide guidelines
  - supporting the formulation of promising search terms for finding biological analogies for a technical problem. Depending on the technical problem, guidelines are given which search term type is most beneficial for searching.
  - supporting the selection of term variations according to their potential of increasing the amount of relevant analogies.
  - supporting a type of technical problem-specific use of the graph-based representations.
- BIOscrabble will provide the possibility to execute graph-based analyses in order support the user in exploring the huge amount of biological information.

- The above mentioned partial outcomes will be based on case studies in which BIOscrabble is applied to a sufficiently large number of different classes of technical problems.
- BIOscrabble will be connected to a platform supporting the transfer of biological solutions into technical solutions that is developed in another research project.

10 FUTURE WORK

To achieve those outcomes, further research has to be done and further case studies with the application of BIOscrabble have to be performed to

- understand possible correlations between types of search terms and relevant biological research articles dependent on specific classes of technical problems.
- understand possible correlations between the use of search term variations and relevant biological research articles dependent on specific classes of technical problems.
- understand possible correlations between the benefit of certain graphs and specific classes of technical problems.
- extend the graphs that are currently proposed.
- to further prove the text source of biological research articles (and the database PubMed), the types of search terms, the term variations (and the software WordNet) and the graphs regarding their value for solution search in bio-inspired design.

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REFERENCES

Chakrabarti A., Sarkar P., Leelavathamma B., and Nataraju B. S., 2005, A Functional Representation for Aiding Biomimetic and Artificial Inspiration of New Ideas, *Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 19(02), pp. 113–132.*

Cheong H., Shu L. H., Stone R. B., and McAdams D. A., 2008, Translating Terms of the Functional Basis into Biologically Meaningful Keywords, *Proceedings of IDETC/CIE 2008 ASME 2008 International Design Engineering Technical Conference & Computers and Information in Engineering Conference, New York City, NY, USA.*

Cheong H., and Shu L. H., 2012, Automatic Extraction of Causally Related Functions from Natural-Language Text For Biomimetic Design, *Proceedings of the ASME 2012 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE 2012, Chicago, IL, USA.*

Chiu I., and Shu L. H., 2005, Bridging Cross-Domain Terminology for Biomimetic Design, *Proceedings of IDETC'05 ASME 2005 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Long Beach, California, USA.*

Chiu I., and Shu L. H., 2007, Biomimetic Design through Natural Language Analysis to Facilitate Cross-Domain Information Retrieval, *Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 21(01), pp. 45–59.*

Eder W. E., and Hosnedl S., 2008, *Design-Engineering – A Manual for Enhanced Creativity*, Taylor & Francis Group LLC.

Erden M. S., Komoto H., Van Beek T. J., D'Amelio V., Echavarria E., and Tomiyama T., 2008, A review of function modeling: Approaches and applications, *Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 22(02), pp. 147–169.*

Gramann J., 2004, *Problemmodelle und Bionik als Methode.*

Hacco E., and Shu L. H., 2002, Biomimetic Concept Generation Applied to Design for Remanufacture, *Proceedings of DETC'02 ASME 2002 Design Engineering Technical Conferences and Computers and In-formation in Engineering Conference, Montreal, Que-bec, Canada.*

Hill B., 1997, *Innovationsquelle Natur*, Technische Universität München.

Kaiser M. K., Hashemi Farzaneh H., and Lindemann U., 2012, An Approach to Support Searching for Biomimetic Solutions Based on System Characteristics and its Environmental Interactions, *International Design Conference - Design 2012, Dubrovnik, Croatia.*

Ke J., Wallace J. S., and Shu L. H., 2009, Supporting Biomimetic Design through Categorization of Natural-Language Keyword-Search Results, *Proceedings of the ASME 2009 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE 2009, San Diego, California, USA, pp. 1–10.*

Ke J., Wallace J. S., Chiu I., and Shu L. H., 2010, Supporting Biomimetic Design by Embedding Metadata in Natural-Language Corpora, *Proceedings of the ASME 2010 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE 2010, Montre-*

al, Quebec, Canada, pp. 1–8.

Löffler S., 2008, *Anwenden bionischer Konstruktionsprinzipe in der Produktentwicklung,* Technische Universität Carolo-Wilhelmina zu Braunschweig.

Mak T. W., and Shu L. H., 2004, Abstraction of Biological Analogies for Design, *CIRP Annals - Manufacturing Technology, 53(1), pp. 117–120.*

Nagel J. K. S., Stone R. B., and McAdams D. A., 2010, An Engineering-to-Biology Thesaurus For Engineering Design, *Proceedings of the ASME 2010 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE 2010, Montreal, Quebec, Canada.*

Nagel J. K. S., and Stone R. B., 2011, A Systematic Approach to Biologically-Inspired Engineering Design, *Proceedings of the ASME 2011 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE 2011, Washington, DC, USA.*

Pahl G., Beitz W., Feldhusen J., and Grote K. H., 2007, *Engineering Design: a Systematic Approach*, Springer-Verlag, London.

Shu L. H., 2004, Generalizing the Biomimetic Design Process, *Proceedings of CDEN/RCCI Inaugural Design Conference, Montreal, Quebec, Canada.*

Shu L. H., 2010, A natural-language approach to biomimetic design, *Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 24(04), pp. 507–519.*

Son J. (Jay), Raulf C., Cheong H., and Shu L. H., 2012, Exploring the Collective Categorization of Biological Information for Biomimetic Design, *Proceedings of the ASME 2012 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE 2012, Chicago, IL, USA, pp. 1–9.*

Srinivasan V., Chakrabarti A., SAPPhIRE – An Approach to Analysis and Synthesis*, International Conference on Engineering Design, ICED09, Stanford, CA, USA*

Stone R. B., and Wood K. L., 2000, Development of a Functional Basis for Design, *Journal of Mechanical Design, 122(December).*

Stroble J. K., Stone R. B., McAdams D. A., and Watkins S. E., 2009, An Engineering-to-Biology Thesaurus to Promote Better Collaboration , Creativity and Discovery, *Proceedings of the 19th CIRP Design Conference – Competitive Design, pp. 30–31.*

Vakili V., and Shu L. H., 2001, Towards Biomimetic Concept Generation, *Proceedings of DETC'01 ASME 2001 Design Engineering Technical Conferences Design Theory and Methodology, Pittsburgh, Pennsylvania.*

Vandevenne D., Verhaegen P.-A., Dewulf S., and Duflou J. R., 2011, A Scalable Approach for the Integration of Large Knowledge Repositories in the Biolog-ically-Inspired Design Process, *International Conference on Engineering Design, ICED11, Copenhagen, Denmark.*

Vandevenne D., Verhaegen P.-A., Dewulf S., and Duflou J. R., 2012, Automated Classification into the Biomimicry Taxonomy, *International Design Conference - Design 2012, Dubrovnik, Croatia, pp. 1161–1166.*

Vandevenne D., Caicedo J., Verhaegen P.-A., Dewulf S., and Duflou J. R., 2012, Webcrawling for a Biological Strategy Corpus to Support Biologically-Inspired Design, *CIRP Design 2012, A. Chakrabarti, ed., Springer-Verlag, London, pp. 83–92.*

Vattam S. S., and Goel A. K., 2011, Foraging for Inspiration: Understanding and Supporting the Online In-formation Seeking Practices of Biologically Inspired Designers, *Proceedings of the ASME 2011 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE 2011, Washington, DC, USA, pp. 177–186.*