Title:
Embedding Biological Knowledge in a Conceptual Design Tool

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Keywords:
Biomimicry, Bio-Inspired Design, Biomimetics

DOI: 10.14733/cadconfP.2015.270-274

Introduction:
Life evolution is estimated in 3.8 billion of years and it is commonly agreed that Nature evolved toward living organisms capable to live with an efficient use of resources [4]. The use of these solutions for technical purposes is old, at least, as the human life. After a long period that begun with the First Industrial Revolution when Nature was indiscriminately exploited, this tendency has found a new blossom in the past decades, when the lack of resources has led scientists to rethink the way we look at Nature in order to learn from it, instead of overworking it [3]. Not surprisingly, in the last fifty years the imitation of Nature has become a multifaceted research topic, as witnessed by the overlapping objectives of Bionics, Biomimetics, Biomimicry and Bio-Inspired Design.

Using Nature as a source of inspiration allows developing breakthrough innovations, but it is worth noting that the process of Biologically-Inspired Design requires multi-disciplinary competences and a different mindset with respect to typical engineering design approaches as Dong well highlighted by describing Bio-Inspired Design as the understanding of design competence from biological evidence [9]. A major limitation of Bio-Inspired Design (BID) is therefore the identification of the most appropriate biological resources suitable for addressing an engineering problem, due to the huge dimension of the information fund and to the lack of a proper guidance for engineers about how to orientate themselves in biological literature. Moreover, the identification of a relevant Natural Source of Inspiration (NSoI) actually requires appropriate biological knowledge and this is one of the greatest limitations to support designers and engineers in producing a Bio-Inspired Design.

This paper proposes a tool for linking the Functional Basis of NIST (US National Institute of Standards and Technology) [10] with the Biomimicry Taxonomy [6] as a way to ease the identification of suitable biological stimuli for addressing a design task.

The use of Nature as a Source of Inspiration:
Nature has been always adopted as a reference and an example one can draw inspiration from. *Natural Shapes* represent a major source of inspiration for new products in the Industrial Design domain [14]. Besides, several domains in science and technology treasured the knowledge that has been “borrowed” from Biology [2]. Evidences of this knowledge transfer can be found in different applications, such as Artificial Intelligence (AI), Smart system controls, Artificial and Bio-Inspired materials and structures, Senses and Sensors, Artificial muscles and mechanism, etc. In this context, Bio-Inspired Design has to be scoped as an activity in which Natural Sources of Inspiration (NSoI) provide the designers stimuli to ideate solutions capable of satisfying specific requirements. Vincent [19] showed that engineering could reuse biological knowledge at different level of abstraction. More abstract the biological concept is (from “total mimicry” to “inspiration”), larger is the effort to adapt it into the engineering field. At

the same time, higher abstraction corresponds to larger opportunities of application. Beyond the above levels of abstraction, whatever is the specific imitation pattern, a designer can follow two opposed approaches to imitate nature.

The Problem-Driven approach starts from a technical problem and requires the designer to search for the most appropriate NSoI that can help solve the specific problem. The Solution-Driven approach, in turn, stems from a biological solution. The designer, then, explores technical problems the Biological Solution at hand can address. Both the approaches result in the definition of bio-inspired product designs. Between the two, the Solution-driven approach represents the less promising path to be embedded into a CAD system, since it does not allow the designer to search and select specific appropriate solutions: the biological source of inspiration is fixed a priori. The Problem-Driven approach, on the contrary, presents better opportunities of harmonization within Computer-Aided Design tools. The path from problem to solution, indeed, reflects the overall structure of the most acknowledged design methods in literature (e.g. [8] and [13]). The main obstacle on this path is that designers usually lack knowledge about natural organisms, as highlighted in Rosa et al. [16].

This paper follows this approach proposing an easy-to-use tool for linking functional design tasks with natural principles. Before entering the details of its features and underlying theory, a brief survey of the relevant studies published so far is hereafter presented.

The literature survey shows a thriving community working in the field and its contributions spread in several research directions. For instance, some scholars are working on bridging terminology for Bio-Inspired Design so as to allow Designers to develop an Engineering-to-Biology thesaurus ([7] [12]). Some others proposed the insertion of metadata in text-based corpora, such as part of speech, in order to improve the search for NSoI with a Natural-Language processing approach ([11] [17]). Rosa, Rovida, & Viganò [18] also proposed a technical functional grammar oriented to Bio-Inspired Design; in turn, Wei, Guozhong, Hui, & Runhua [20] stressed the opportunities deriving from a symbol-based search. Other scholars are working on the development of ontologies specifically tailored for the BID approach [15]. The following Sections presents the authors' contribution for a methodological tool to improve the usability of databases for searching NSoI. Its overall structure has been conceived to be easily embeddable into a Computer-Aided System for Conceptual Design.

A methodological tool to search for NSoI:

The proposed tool is part of a complete methodology for Bio-Inspired design proposed in [1] and it represents the research outcome that can be directly embedded into a CAD system. The tool leverages the information and data provided by the Biomimicry Institute database, Asknature. It collects biological effects/phenomena that are classified consistently to a functional taxonomy. Unfortunately, the mismatching definition of groups and functions between biology and engineering makes this matching very difficult for engineering designer. Engineering designers typically describe system functions according to two main perspectives, models based on functions as actions aimed at transforming energy-material-signal flows [13] and those characterized by a triad tool-action-object [6]. The NIST Functional Basis is organized consistently with the first approach and technical functions can be modeled as action-flow couples. The authors analyzed the correlations between models describing natural and technical systems, to integrate bio-effects as sources of inspiration in design. The outcomes of such a correlation analysis have been organized in a conversion table, whose logic is summarized in Figure 1.

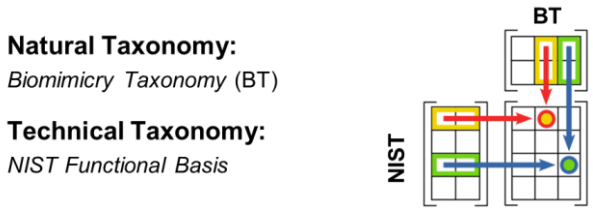

Fig. 1: Schematic representation of the conversion table between the Functional Basis and the Biomimicry Taxonomy.

Experimental investigations:
Several experiments have been conducted to assess the benefits and the usability the proposed linking table. The initial experiments are available with full details in [1], where the entire design process from problem framing to concept development is analyzed. The experimental validation has been carried out with a set of relevant potential users of the methodology, namely design engineers in their final semester of the MS in Mechanical Engineering at Politecnico di Milano. The testers were gathered on a voluntary basis among the students attending the course on Methods and Tools for Systematic Innovation in 12/13. Nineteen (19) students agreed to participate the experimentation, allowing authors to focus the analysis on the knowledge gap produced by an unsupported approach and the authors' proposal in the same subject. Tester number is also sufficient to obtain statistically significant results.
As test case, the designers have been asked to develop an original solution for bicycle luggage rack for city bike sharing systems, a design task well known in the engineering design education community. In order to carry out the experiment, each of the testers were asked to complete three different tasks concerning the identification of NSoI that turn to be useful to solve the design problem. By pertinence, the three tasks can be divided into two groups:

a. A free and unconstrained search in the AskNature.org database;
b. A methodology-supported search strategy to make the retrieval of NSoI that is composed by two sub-steps:
    1. The description of the design problem consistently with the NIST Functional Basis;
    2. The use of the NIST2BT correlation matrix to check the more effective accessibility of the BT by designers so as to drive their new searches on AskNature.org.

The following paragraphs describe these three tasks by presenting, for each of them, the purpose of the specific investigation, the obtained results and the inferred findings.

Free search in AskNature.org (a)
Results of this first test have been firstly analysed considering the single keywords composing the queries. They have been classified according to two main categories. The first one characterizes the keywords depending on what they refer to, between Problem Description and Solution. Secondly, the queries have been also investigated as a whole, in order to highlight specific behaviours and biases of designers. As a result of these analyses, it clearly appeared that when the design engineers, participating the test, freely query the database in search Natural Sources of Inspiration, they preferentially choose technical keywords, and quite commonly choose keywords related to the characteristics of the specific solution for the technical problem. It also emerged that the choice of using "technical" keywords about problems enables the designers to retrieve NSoI about already existing Bio-Inspired Products. This suggests that technical keywords do not lead to authentic NSoI, but more likely provide DB records of products embedding natural characteristics that have been already implemented. This conclusion enforces the need of an appropriate approach to query the database. Next sections summarize the main steps of the proposed approach.

The description of the Technical Problem in NIST terms (b1)
The NIST functional basis is proposed as the starting step of the search approach. Specifically this second test investigates the following issue: Does designers produce repeatable results by describing problems with the NIST Functional Basis? A positive answer to the above question is a key point for a proficient use of the BT-NIST correlation matrix, being the problem description the input to translate the technological demand into a biological-related one. From the comprehensive analysis of the results of this experiment, it clearly emerges that not all the testers felt the need of characterising the model by both the action and the flow. All the designers have identified one or both classes of the NIST functional basis useful for the description of the given technical problem. More than one fourth of the designers described the action underlying the problem as "Connect – Couple – Link" that turns out to be a not fully satisfactory description for the technical problem at hand. These results push for a careful definition of the problem in NIST terms to maximize the effectiveness of applying the NIST2BT correspondence matrix.

The use of the BT-NIST correlation matrix (b2)
The problem-based approach requires the designers to search for a meaningful NSoI in the biological domain. This implies the correlation matrix has to be robust and easily usable. This test, therefore, aims at verifying the following question: Is the correlation matrix robust in the translation of a given problem in biological terms? To this purpose, each tester has been asked to use the outcomes of its previous test and formulate the same problem in biological terms, with the NIST2BT correlation matrix. Table 1 summarizes the outcomes of the test. The overall count of answers exceeds the overall number of testers because the same NIST functional description might span more than one biological challenge or strategy of the Biomimicry Taxonomy. The considerations in the column "Notes" show that great majority of testers correctly used the correlation matrix once they have a proper input to access it.

Group	Sub-Group	*(Natural)* Function	Count	Percentage	Notes
Make	**Physically Assemble**	**Structure**	15	45%	Acceptable
Move or Stay Put	**Attach**	**Temporarily**	14	42%	Acceptable
Move or Stay Put	**Attach**	**Permanently**	3	9%	biological description not consistent with temporary nature of problem (it's not permanent)
Make	**Chemical Assemble**	**Attach**	1	3%	Total misunderstanding

Tab. 1: Again, short captions should be centered under each table.

BID and CAx integration:
The collocation in the Pahl and Beitz approach of the above discussed design tool appears to be the Conceptual Design Stages. Hence, its practical deployment could result in a series of dropdown menus, from which users can select the terms (verbs and objects) to compose the sought function, or expandable trees (as in [18]), in which users can locate the function to be accomplished, so that the system can automatically supply a set of candidate NSoI. Moreover, this system can be directly connected to the PDM system, in order to allow designers to easily retrieve the complete documentation of products previously developed starting from a particular NSoI.

Conclusions:
The presented approach is structured into two main steps: the design problem is firstly formalized as a functional demand consistent with the NIST Functional Basis. Then, it is translated into a functional query expressed in biological terms. For this specific purpose, authors conceived a matrix correlating technical (NIST-based) and biological description (according to the Biomimicry Taxonomy) of functions, as a key tool allowing an effective formulation of problems for design engineers having no or poor biological knowledge. The capability of this approach has been tested against an unsupported search of relevant natural sources of inspiration from the same DB. Results shown that this approach substantially makes BID approach more effective for engineering purposes. According to these research outcomes, the authors expect to continue the development of this kind of tool by exploiting the recent advancements in the field of computer-based conversational agents. An investigation of the technical problem by predefined questions and answers might ease the identification of the appropriate NIST description, so that the transfer from technology to biology might occur in background resulting in ready to use queries to question biological databases where to look for solutions or, simply, inspiration.

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