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Embedding biological knowledge in a conceptual design tool

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ABSTRACT
This paper presents a methodological tool to support the search for Natural Sources of Inspiration so as to spark new ideas in designers along Bio-Inspired Design activities. The proposed tool leverages the correlation between the NIST Functional Basis and the Biomimicry Taxonomy, to allow designers with no or scarce biological knowledge to search already existing databases of natural phenomena. The methodological framework is structured so that its implementation in a CAx system can be promisingly carried out.

KEYWORDS
Biomimicry; Bio-Inspired Design; Biomimetics

1. Introduction

Life evolution is estimated in 3.8 billion of years and it is commonly agreed that Nature has evolved toward living organisms capable to live in extreme environmental conditions with an efficient use of resources and characterized by the deployment of very elegant solution strategies [5]. 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 [4]. 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 [13].

A major limitation of Bio-Inspired Design (BID) certainly is 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. Not surprisingly, the most acknowledged consulting services operating with biomimetics are run by biologists, or at least by experts with a solid background in biology. This characteristic certainly constitutes a crucial bottleneck to the extensive adoption of biomimetics in industrial R&D activities. 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. Furthermore, an incomplete understanding of the biological system or phenomenon at hand reduce its potential advantage on the problem to be solved.

With the ultimate goal of contributing to the successful and efficient adoption of BID practices by designers and problem solvers with a traditional engineering background, this paper proposes a tool for linking the Functional Basis of NIST (US National Institute of Standards and Technology) [17] with the Biomimicry Taxonomy [6] as a way to ease the identification of suitable biological stimuli for addressing a design task.

The paper is structured as follows: the next section summarizes strengths and weaknesses of the BID approaches the authors have examined from literature. Stemming from the current limitations of these approaches in supporting designers with no biological knowledge to access biological sources of inspiration, the authors propose a two-step path to translate technological problems into biological ones. This approach has been tested against an unsupported usage of the AskNature BID engine (www.asknature.org). The last section

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before the conclusion summarizes the outcomes of the experiment. The authors close the paper by discussing the applicability of this approach into a Computer-Aided Design system.

2. 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, in order to solve problems. *Natural Shapes* represent a major source of inspiration for the development of new products in the Industrial Design domain [22]. For instance, Luigi (Lutz) Colani and Jean-Marie Massaud produced several designs recalling natural shapes. Nevertheless, those proposals just recall the external appearance of living beings without any attempt to really integrate in the design different features concerning, e.g., principles and functions by which these organisms live. Besides, several domains in science and technology treasured the knowledge that has been "borrowed" from Biology [3]. 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 perspective, it is not surprising that nowadays industries are more and more interested in the opportunities offered by Bio-Inspired Design research. Natural sources of inspiration, indeed, started permeating different organizational level in order to achieve various goals for the company strategy. In fact, Jasper [18] recognized the importance of proposing products characterized by a "Natural soul" in order to improve their market appraisal. Therefore, it is not surprising that Nature has usually left his sign on marketing and advertisement campaign, rather than really characterizing the design of a product. From the perspective of product design, however, those activities lay beyond the scope of this paper. Bio-Inspired Design, in this context, 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 [33] showed that engineering can reuse biological knowledge at different level of abstraction. More abstract the biological concept is (from "total mimicry" to "inspiration" in Figure 1), 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 (Figure 2).

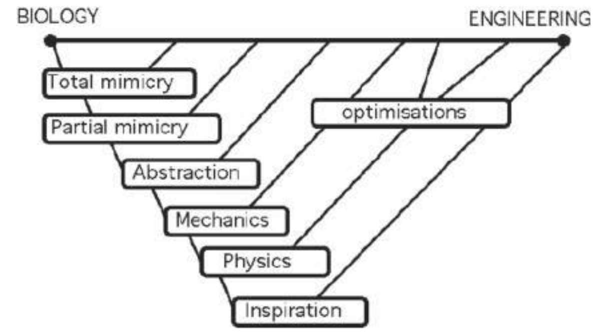

Figure 1. A biomimetic "map" to illustrate the idea that the more abstract a concept is, the more adaptable it is within another discipline (Vincent 2001 [33]).

The Problem-Driven approach (above) 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 (bottom), 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 require the designer to search and select specific appropriate NSoI: the biological source of inspiration is already known, a priori. The search, here, deals with technical problems still requiring a solution. As witnessed by Helms et al. [15], these technical problems can be very distant from the motivation behind the selected natural solution and the search might be really ineffective due to its intrinsic unstructured nature.

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. [12,21]). With a plan of design objectives and product requirements, designers first define problems and subsets of them to focus on candidate functions, working principles and structural characteristics for the solution.

For these reasons, the goal-based nature of the Problem-driven approach seems to be more promising in order to improve both the efficiency of the design process and the effective capability of producing meaningful results along the development of a solution using a CAD tool. Despite this, the existence of an enormous variety of natural systems and phenomena can lead to searches (for NSoI) producing unmanageable and, worse, non-meaningful results. Moreover, designers usually lack knowledge about natural organisms, which makes the identification of a meaningful NSoI tougher and tougher, as highlighted in Rosa et al. [25]

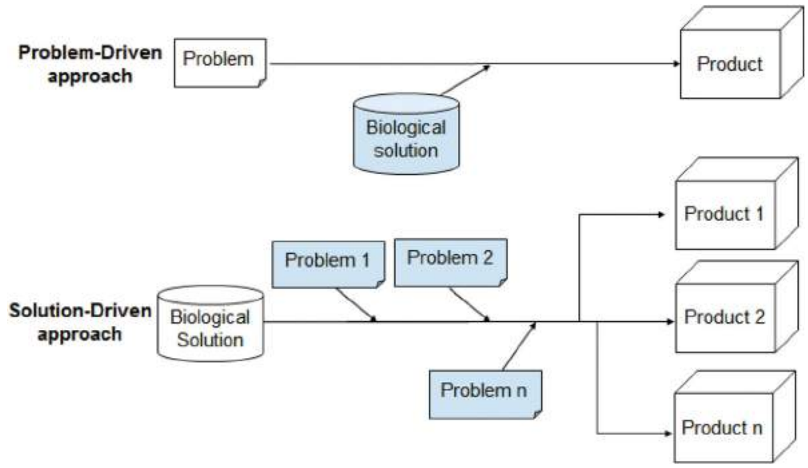

Figure 2. Problem-Driven approach and Solution-Driven approach for BID (S. Schenkl et al., 2011, [27]).

This said, whatever the approach is, Bio-Inspired Design requires multi-disciplinary competences to be successfully carried out. To this purpose, several scholars are developing methods and tools to support engineering designers in a more effective and efficient identification of NSoI along their design tasks.

This paper follows this stream proposing a easy-to-use tool for linking functional design tasks with natural principles, mostly tailored for problem-driven tasks, but possibly usable also for solution-driven approaches. Before entering the details of its features and underlying theory, a brief survey of the relevant studies published so far is here presented.

2.1. Literature survey

The literature survey shows a thriving community working in the field and its contributions spread 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 ([11,20]). 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 ([19,28]). Taylor, Rosa, Rovida, & Viganò [30] also proposed a technical functional grammar oriented to Bio-Inspired Design; in turn, Wei, Guozhong, Hui, & Runhua [35] stressed the opportunities deriving from a symbol-based search. Among the reviewed contributions, three main strategies to enable designers and technician to access and use biological knowledge emerged. They are summarized in the following.

2.1.1. Database approach

The database proposed by AskNature and Bionics2Space (respectively available at http://www.asknature.org/ and formerly available at http://atlas.estec.esa.int/bionics2space/), are two of the existing collections of biological effects/phenomena classified according to a specific functional taxonomy. Designers usually deal with needs and functions and create links between them (e.g." by carrying out the function X it is possible to satisfy the need Y") and this is probably the reason behind the larger adoption of this kind of approach if compared to others. Despite that, it is quite uncommon to find biological literature describing living organisms in terms of (engineering) functions. In addition, as discussed in [26], the transfer of knowledge from biology to engineering can be reference to four main classes: parts and materials (i); organs, physical effects, phenomena and state changes (ii); attributes (iii); actions and functions (iv). This means the current databases are suitable just to transfer knowledge for the last of the above four classes. Moreover, the search results usually provide too many responses to typical queries for specific design objectives. This make this approach potentially inefficient considering that all the occurrences of the search results should be evaluated in terms of relevance to the design related query. Beyond the above limitations, this approach still represent one of the most effective option, as witnessed by its adoption by the European Space Agency (ESA) to support the development of breakthrough solutions for space research and space flight within its Advanced Concept Team (ACT) [14].

The effectiveness of this approach is also testified by the strong and continuous evolution of new data structures aimed at evolving this database from "unstructured" to "structured" (i.e. explicitly describing organs, physical effects and phenomena, state changes, attributes, actions and functions), in order to overcome the above-described limitations. In particular, this approach is followed by Chakrabarti et al. [10] who developed the SAPPHiRE causal model, Vattam et al. [32] who developed the DANE software and functional models, and also by Rosa et al. [23] who are working to evolve by synergically merging previous efforts.

2.1.2. *Text-mining approach*

The Text-Mining Approach aims at exploiting "the large amount of biological knowledge" that is already available in trustworthy sources "rather than creating an enormous database of biological knowledge to specifically support engineering design" [11].

The gap between biologists' and engineers' language and vocabulary represents one of the greatest limitation of this approach and it is common to face situations in which the latter completely submit useless keyword because of semantic distance between domains. To address this issue, scholars from Toronto University proposed an algorithm to "generate a non-obvious keyword provided by a domain expert as one of many other non-obvious but relevant keywords". The text miner scans one single source: "Life. The science of biology". This approach leveraging computational linguistics has a great potential, but the current availability of computational power makes it not scalable for its extensive application to a larger set of biological sources.

Stroble et al. [29] followed a similar approach. They generated a thesaurus containing biologically connotative terms related to engineering functions and flows (i.e. what a function transforms). The structure of the thesaurus follows the reconciled Functional Basis by NIST [17] so that the biological knowledge can be more conveniently used by engineers and designers.

Besides, a significant step ahead in the direction of scaling up this approach towards the analysis of huge biological repositories has been presented by Vandevenne et al. [31] and this makes the text mining approach very promising for future developments of BID.

2.1.3. *TRIZ approaches*

Firstly, Altshuller, author of the theory of inventive problem solving – TRIZ in Russian, suggested to look at biological systems to get inspired, although "yet only a tiny fraction of Nature's inventions are used" [1]. Prehistorical animals, that he considered simpler, were suggested as a good source to draw inspiration from and to create evolutionary analogies with technical systems.

Vincent et al. followed this Altshuller's research streamline and selected TRIZ logic to transfer "knowledge between different scientific and engineering disciplines" [34], [8]. Their Bio-TRIZ Matrix stems from the TRIZ Matrix of Contradictions. TRIZ contradiction, in turn, is the core of the Bionic-Oriented Construction Process by Hill, where goal setting is carried out through contradiction analysis [16]. Both the approaches requires the definition of a contradiction in order to identify an appropriate biological inspiration. The former focuses on contradictions between resources (as information, energy, time, space, structure and substance) both in natural and technical systems. The latter organizes contradictions according to a functional basis, allowing to extend the search from resources to specific natural solutions and strategies.

The following part presents the authors' contribution for a methodological tool to improve the usability of databases for searching NSoI. Its overall structure has been conceived so that it is possible to embed the methodological steps into a Computer-Aided System for Conceptual Design.

3. A methodological tool to search for NSoI

The proposed tool is part of a complete methodology for Bio-Inspired design proposed in [2] 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. As mentioned above, it collects biological effects/phenomena that are classified consistently to a functional taxonomy. More specifically, the taxonomy is organized according to "challenges" and "strategies" the organisms respectively meet and adopt to keep surviving. Table 1 shows an example of the hierarchical structure of the Biomimicry Taxonomy (BT).

Unfortunately, the mismatching definition of groups and functions between biology and engineering makes this instrument difficult for engineering designer to be proficiently used.

Indeed, engineering designers typically describe system functions according to two main perspectives, models based on functions as actions aimed at transforming energy-material-signal flows [21] and those characterized by a triad tool-action-object [9]. The NIST Functional Basis is organized consistently with the first approach and technical functions can be modeled as action-flow couples.

The basis for actions is structured into:

- 8 main classes (more generic actions)
  - 21 secondary classes;

Table 1. Structure and exemplary record (title) of the Biomimicry Taxonomy.

Biomimicry Taxonomy	Examples
Group	Maintain physical integrity
Sub-Group	Protect form biotic factors
Function	Protect from animals
Strategy	Nanoscale protrusion

- 24 tertiary classes of actions on flows (more detailed actions).

Flows, in turn, are structured into three distinct categories:

- Material flows (further subdivided into 6 secondary and 11 tertiary specifications);
- Energy flows (further subdivided into 12 secondary and 4 tertiary specifications);
- Signal flows (further subdivided into 2 secondary and 7 tertiary specifications).

This knowledge organization allows a designer to univocally distinguish technical systems according to the functions they carry out. This is a crucial aspect to be leveraged in order to facilitate knowledge transfer from Nature to technology, since a technological demand (for a function) can be expressed at an abstract level of description. This problem model, expressed in terms of needed function, indeed, reduces the distance with the abstract descriptions of solutions in the BT. Therefore, it reduces both the gap between the engineering and the biological domain and the risk of misapplications of natural solution (or the wrong interpretation of NSoI) in the process of inventive design [32].

In order to create a bridge linking the Functional Basis and the Biomimicry Taxonomy, a mapping of the latter to actions and flows of the NIST Functional Basis has been carried out [2]. Then, the authors analyzed the correlations between models describing natural and technical systems, to integrate bio-effects as sources of inspiration in design.

Considering the whole Biomimicry Taxonomy (BT) with reference to the NIST actions, they show a promising degree of correlation, even if some mismatches are present in each of the BT Groups. The only BT Sub-Group having 100% relative match, is the group "Make".

- Exact Match: 57.7%
- Partial Match: 38.8%
- No Match: 3.5%

Sub-groups in the Biomimicry Taxonomy are often described at a high general level that makes difficult dealing with a univocal NIST action. For instance: The BT sub-group "Modify, Modify Physical state, Size/Shape/Mass/Volume" can be linked to more than one NIST Action, such as Increment, Decrement, Shape, Condition, the whole set of secondary levels of Control magnitude, Change. On the other hand, sub-groups can just partially match to the NIST Actions because these contain complementary information about the action (e.g some BT descriptions involve both action and flow). For example, the BT sub-group (Move or Stay Put, Move, *In/On Liquid*) could be put into correspondence with the NIST Action (Channel, Transfer, Transport). Moreover, BT groups presenting reflexive actions (e.g. self-doing something) cannot be linked to NIST because reflexive actions cannot be described consistently with the action-flow engineering functional model. In other cases, BT sub-groups are related to relevant biological processes that not necessarily find an engineering correspondent, such as (Process Information, Sense Signals/Environment Cue, Body Awareness) which just partially match the NIST Action (Signal, Sense, Detect/Measure). Indeed, as shown in the above bullet list, non-matching element ratio is relatively low; the lack of correspondence between the two classification is mostly due to what is considered a function by biologists and cannot be defined with an action-flow model so that it is meaningful and still formally correct (e.g. BT (Maintain Community, Coordinate, Activities).

Downwards this analysis, the authors synthesized a conversion table (Figure 3) to link technical functions with the relevant groups and sub-groups of the Biomimicry Taxonomy (available at [6]). This allows designer to formulate a technical problem according to the scheme "How to deliver the function . . . ?". This function, then, can be expressed consistently with the NIST Functional Basis and finally, by means of the conversion table, to be turned into a meaningful query to search for NSoI within the Biomimicry Taxonomy. Eventually, this results in a set of relevant natural strategies as the search engine retrieve information from the AskNature DB. The entire process is suitable, given the nature of the NIST2BT conversion table, to be embedded in a software module for supporting conceptual design activities.

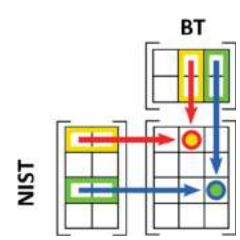

Figure 3. Schematic representation of the conversion table between the Functional Basis and the Biomimicry Taxonomy.

4. Experimental validation

Several experiments have been conducted to assess the benefits and the usability of the selected models and the proposed linking table. The initial experiments, as briefly mentioned at the beginning of previous section, are available with full details in [2], where the entire design process from problem framing to concept development is analyzed.

This paper focuses on studying the following specific aspects:

- The search by keywords by designers without Biological Knowledge in AskNature.org
- The problem description by using the NIST Functional Basis
- The use of the correlation matrix NIST-BT

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 2012–2013. Nineteen (19) students agreed to participate the experimentation. Considering the number of participating subjects, the experimental activity has been carried out as a "within group" test, rather than a "between groups" one, so as to satisfy several conditions:

1. To allow the analysis to focus on the knowledge gap produced by an unsupported approach and the authors' proposal in the same subject, so as to obtain "local" measures of the potential benefit it generates
2. To have a sufficient number of testers in the group, so as to obtain results which might have some statistical significance.

As test case, the designers have been asked to develop an original solution for a design task well-known in the engineering design education community, i.e. the bicycle luggage rack to be employed in a city bike sharing system, as shown in Figure 4.

In order to carry out the whole experiment, each of the 19 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 in order 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.

4.1. Free search in AskNature.org (a)

4.1.1. Purpose

The AskNature.org database has been fed (and actually its size is continuously growing due to new contributions) with information about natural phenomena that biologists have properly organized into functional categories.

The database is easily accessible, due to its online nature, from everywhere and by everyone, whatever is its expertise or profile (i.e.: biological knowledge is not required). Accessibility, nevertheless, does not imply usability. This first task, therefore, aims at investigating the following questions:

- Is the DB proficiently usable by designers having no or poor biological knowledge (e.g. from high school classes)?
- Do designers require specific guidelines to get support for using of the database?

The testers were asked to access the database and formulate queries with the purpose of finding relevant

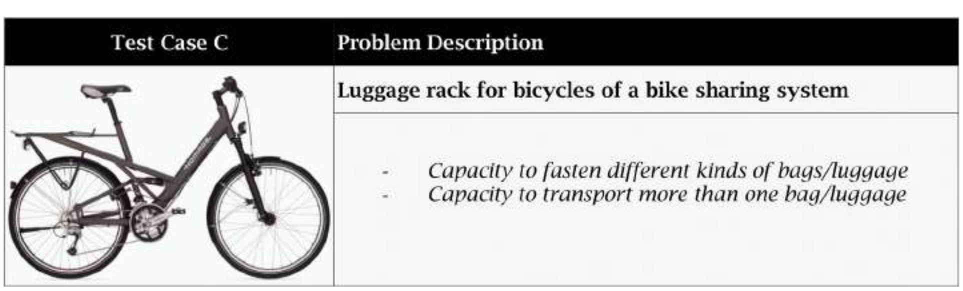

Figure 4. The concise design brief the testers were provided with, before starting the test.

NSoI, without any further constraint. In other words, testers receive no other input than the test case design brief, so that the choice of keywords is up to each participant. Testers have the faculty to try more queries.

4.1.2. Results

Results 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 (i.e. keywords referring to an objective to be achieved);
- Solution (i.e. keywords related to a strategy to achieve an objective).

Keywords, have been also characterized consistently with the following clusters

- Functions (i.e. actions aimed at carrying out a transformation on a flow – green cells);
- Properties (i.e. intrinsic or extrinsic features of an entity, potentially conferred by a function – yellow cells);
- Others (i.e. the residuals of function and properties – pink cells)

Table 2 summarizes in an aggregated way the different keywords used for the queries, together with the abovementioned characterization.

In addition to the above analysis, the queries have been also investigated as a whole, beyond their granular constituents (keywords), in order to highlight specific behaviours of designers to retrieve the information from the AskNature.org database.

More in detail, queries have been studied considering the overall amount of keywords used. Figure 5 shows some examples of query that are also classified considering if they refer to problem descriptions or technical solutions.

Table 2. Keywords used in the free search of the AskNature.org database.

Keywords	Count	Problem (P) or Solution (S) Description	Keywords	Count	Problem (P) or Solution (S) Description
Bag(s)	16	S	Fasteners	1	S
Bike/Bicycle	14		Fix	1	P
Fasten	8	P	Grocery	1	
Luggage	5	S	Immobilize	1	P
Hold	5	P	Keep	1	P
Attach	3	P	Lock	1	P
Fast(en)	2	P	Move	1	P
Object(s)	2	P	Pull	1	P
Plastic	2		Rack	1	S
Transport/ Transportation	2	P	Recycle	1	
Weight	2	P	Sharing	1	
Adhesion	1	P	Shopping	1	
Adhesive	1	S	Smooth	1	P
Block	1	P	Surface	1	P
Carry	1	P	Trash	1	

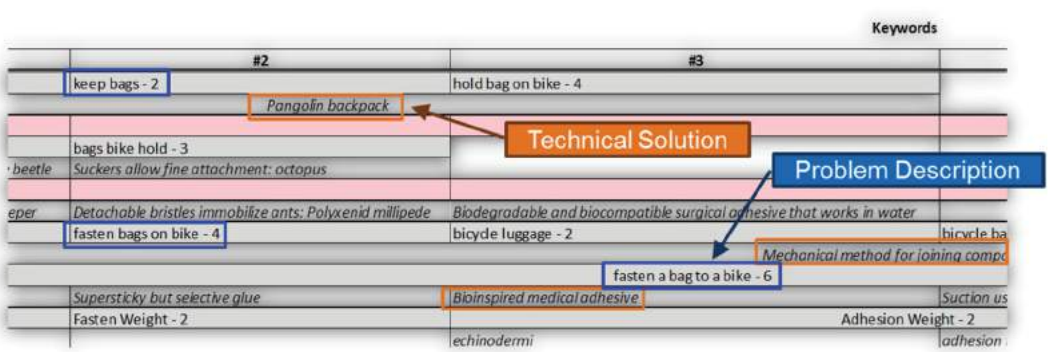

Figure 5. Examples of search queries.

Table 3. Keywords used in the free search of the AskNature.org database

Number of words	Count	Percentage
6	3	8%
5	1	3%
4	5	14%
3	4	11%
2	13	36%
1	10	28%

Table 3, in turn, reports the overall count of queries composed by one or more keywords.

4.1.3. Findings

Considering the above results, it clearly appears that when the design engineers, participating the test, freely query the database in search Natural Sources of Inspiration, they

- Preferentially choose technical keywords in spite of biological- or natural-related ones (e.g. "bags" and "luggage", instead of a more generic and natural laws related "load" or "weight");
- Quite commonly choose keywords related to the characteristics of the specific solution for the technical problem (e.g. "bags" counts 16 occurencies)

Moreover, the amount of keywords used in a single query should be considered, on average, excessive, especially if one considers that the AskNature search engine juxtapose keywords with the AND Boolean operator, thus implying that some relevant NSoI can be missed due to excessive search constraints.

With reference to the examples of Table 5, one can also note that the choice of using "technical" keywords about problems enables the designers to also retrieve NSoI about already existing Bio-Inspired Products as, for instance, the Bio-Inspired adhesive tape and the Pangolin backpack. These products, indeed, represent exemplary records for the DB to facilitate the users understanding how a NSoI might be applied in order to synthesize/ideate a Bio-Inspired product. 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.

Furthermore, the experiment shows that designer poorly exploit the opportunities offered by the database. The unconstrained or non-driven definition of keywords produces various and non-homogenous results: from those extremely relevant, to those that can poorly work as NSoI for the technical problem at hand. In addition, the NSoI belong to a large number of different functional classes, reducing the effective and efficient replicability of the results, whose quality is here mostly due to the personal talent and abstraction skills.

This said, the keywords choice shows that designers, despite dealing with a biological database, use its information about natural phenomena as a repository of technical solutions. This implies the need of an appropriate approach to query the database. Its basic steps, as proposed by the authors, have been tested along the task described in the two following sub-paragraphs.

4.2. The description of the technical problem in NIST terms (b1)

4.2.1. Purpose

The NIST functional basis is here proposed as the starting step of the search approach. Its modelling perspective is here used as proposed in literature and it is necessary to check its usability by design engineers. More specifically the 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 (as a pair "action + flow", or just "action") the input to translate the technological demand into a biological-related one.

Thus, the test requires designer to transform the problem into a functional model according to the NIST Functional Basis.

4.2.2. Results

Tables 4 and 5 respectively show the results of the above presented test. The former collects the set of provided answers about "actions", together with the overall number of occurrences and their ratio.

The latter, in turn, presents the same data for what concerns flows to be considered for the technical problem at hand.

From the conjoint analysis of these two tables, it clearly emerges that not all the testers felt the need of characterising the model by both the action and the flow. Indeed, just 13 of them describe the problem that way, the remaining 6 testers were satisfied by the description provided just by the action. As one can expect, no descriptions were provided just in terms of the flow, being missing the main part of the technical demand (with no verb, there is no clue about what to do with that flow).

4.2.3. Findings

The designers have identified one or both classes of the NIST functional basis useful for the description of the given technical problem with no exceptions.

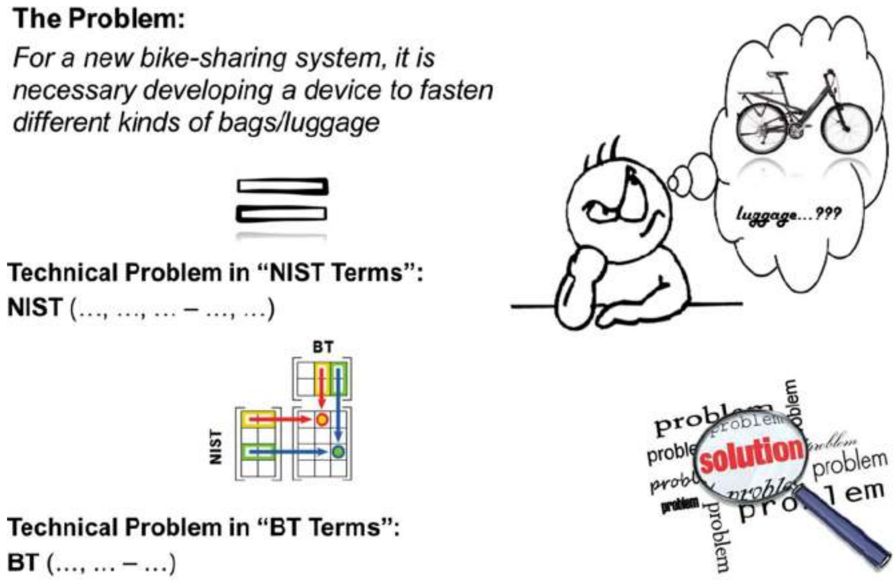

Figure 6. Overview of the translation process of a Technical Problem into Biological Terms.

Table 4. Functional classes used by testers to describe technical problem in NIST terms

Class (*primary*)	Secondary	Tertiary	Count	Percentage
Connect	Couple	Join	8	40%
Connect	Couple	Link	5	25%
Connect	Couple	Join/Link	7	35%

Table 5. Flows used by testers to describe the technical problem in NIST terms

Class (*primary*)	Secondary	Tertiary	Count	Percentage
Material	Solid		1	8%
Material	Solid	Object	12	92%

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, as witnessed in Table 6.

With reference to the proposed approach to drive the definition of queries to question the Biomimicry Taxonomy DB, the results push for a careful definition of the problem in NIST terms to maximize the effectiveness of applying the NIST2BT correspondence matrix.

Table 6. Excerpt of the NIST basis reconciled function set

Class (*primary*)	Secondary	Tertiary	Correspondents
Connect			*Associate, Connect*
	Couple	Join	*Assemble, Fasten*
		Link	*Attach*

4.3. The use of the BT-NIST correlation matrix

4.3.1. Purpose

The problem-based approach presented in the previous section, downwards the problem definition with the NIST functional basis, 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 for supporting the definition of appropriate queries providing relevant results.

This test, therefore, aims at verifying the following question:

- Is the correlation matrix robust in the translation of a given problem into 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.

4.3.2. Results

Table 7 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.

4.3.3. Findings

The above data analysis shows that testers used the correlation matrix as an easy tool once they have a proper

Table 7. Technical problems in Biological terms due to the application of the BT-NIST correlation matrix.

Group	Sub-Group	(*Natural*) Function	Count	Percentage
Make	Physically Assemble	Structure	15	45%
Move or Stay Put	Attach	Temporarily	14	42%
Move or Stay Put	Attach	Permanently	3	9%
Make	Chemical Assemble	Attach	1	3%

input to access it. Just one of them completely misunderstood how to use it, pointing to a biological description which is not related to the NIST functional description defined a few minutes before. Moreover, 3 testers translated the problem by choosing a biological description of the function which is not consistent with the overall objective of the problem. Indeed, the fastening systems should not carry out the function to "Move or Stay Put – Attach – Permanently", it should better allow bike sharing customers to have a solution for doing the same on a temporary basis.

5. BID and CAx integration

This paper presents an approach to support design engineers in the identification of relevant sources of inspiration from nature, in order to get insights to spark off breakthrough ideas borrowed from efficient natural system and develop Bio-Inspired Products. Considering the main limitations characterizing the approaches to support Bio-Inspired Design, the authors introduce a tool, which is part of a more comprehensive design methodology [2], whose structure and repeatability make it suitable for a quick computer implementation in a Computer-Aided (conceptual) Design system. In particular, since the aim of the presented approach has been conceived to assist designers and engineers to search for working principles capable to accomplish a given function, its collocation in the Pahl and Beitz approach appears to be the Conceptual Design Stage (as discussed in [24]). 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 [25]), 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 of the company, in order to allow designers to easily retrieve the complete documentation of products previously developed starting from a particular NSoI, easing designer task and avoiding the re-design of already studied and successfully solved problems.

6. Conclusions

The presented approach, indeed, is structured into two main steps: a design problem should be firstly formalized as a functional demand consistent with the NIST Functional Basis. Then, it has to be translated into a functional query expressed in biological terms. For this specific purpose, the authors propose the adoption of 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 the approach to drive the proper definition of queries for the AskNature.org DB has been tested against an unsupported search of relevant natural sources of inspiration from the same DB. The results have shown that the approach substantially shifts the usability of the Biomimicry Taxonomy, making it more effective also 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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