An approach to validation of technological industrial design concepts with a bionic character

DENIS A. COELHO, CARLOS A. M. VERSOS
Technological Industrial Design Program, Department of Electromechanical Engineering
University of Beira Interior
Calçada da Fonte do Lameiro, 6201-001 Covilhã
PORTUGAL
denis@ubi.pt http://webx.ubi.pt/~denis/MDIT/index.htm

Abstract: Various approaches that are based on the consideration of systematic procedures for the creation of new concepts inspired by nature, following both an information flow that is oriented in a top-down manner from the problem to the solution, and that is oriented in a bottom-up manner from the solution to the problem have been proposed and are available in several literature sources. From the existing methods, a selection of three methods oriented form the problem to the solution was considered for analysis considering their expected support to enable achieving five design goals, considered both typical and encompassing of design projects that seek inspiration form nature. These goals were deemed representative of the high level aims that are pursued by those employing a nature inspired approach to generation of solutions to design problems, even if each and every one of the goals considered may not necessarily be present in every single design project. A major area with lack of support given by the three methods detected was support to verification procedures, enabling the verification of the level of achievement of the goals sought. Therefore, for enhanced support to the use of the three methods scrutinized, within systematic approaches to design, a validation process with tangled steps is presented, encompassing the five goals identified for design based on analogies with biological solutions.

Key-Words: design goals, design methodology, bionic design, systematic approach to design

1 Introduction
The present day’s urgency in achieving environmental sustainability has promoted renewed interest on gathering inspiration from nature in order to create novel design concepts. Design endeavours in several technical disciplines may lead to ground-breaking new concepts when natural systems are considered as a source of inspiration. The focus of this paper is on joining a bionic approach to the creation of industrial design engineering concepts with a systematic approach to design. The conduction of industrial design engineering projects is inherently structured and supported by methods set forth in the systematic design literature (e.g. [1], [2], [3], [4], [5]). Hence, in order to be useful and of practical value to the generation of industrial design engineering concepts, bionic design methods should be able to fit into design endeavours that follow a systematic approach to design.

The main purpose of bionics is to carry out a benchmark of nature, of what it created, tested and has evolved over millions of years, in order to improve what man creates artificially [6]. Three bionic design methods, following an analytical direction that involves seeking inspiration in nature to solve a given problem, were retrieved from literature and are summarily presented. These methods are analysed in this paper with regard to their perceived capacity to support the attainment of the five chosen high level design aims. These aims were selected considering their high degree of perceived relevance to industrial design engineering problems. A critique of the bionic design methods retrieved is laid out, informed by comparison between the methods regarding their ability to support the attainment of the goals. To this follows the proposal of a validation approach. This approach is intended to enable the evaluation of outcomes attained with the use of bionic design methods, offering methodological support to designers in order to pursue the validation of bionic concepts generated by them. A specific design case is presented with the purpose of exemplifying the application of the validation steps proposed. The requirements initially considered for the development of the product functionality considered in the case are presented and a solution that is proposed to fulfil these requirements, generated using a bionic approach, is evaluated, according to the validation approach presented.
2 Existing methods to support the generation of bionic design concepts for the solution of a given problem

Three existing methods to support the generation of bionic design concepts for the solution of a given problem, retrieved from literature, were analyzed, and are presented in Table 1 through Table 3. These share a common direction of analysis, which departs from a given problem and seeks the proposal of solutions by gathering insight and inspiration from natural systems. This approach begins with the identification of a problem or the needs of a project, which is followed by looking for inspiration from nature or seeking an analogy with a natural solution to foster the emergence of a solution to the problem (a bionic solution proposal).

The method presented in Table 1 provides a detailed description of the procedures involved in natural sample collection and analysis. It also prescribes completely listing the working principles of the natural system. However, this method does not include any procedures concerning the design transfer of the features found in the natural samples. The design method presented in Table 2 gives emphasis to the product life cycle, by giving consideration to issues such as manufacturing processes, packaging and recycling of the product in development. In this method, iterations are implicit, and evaluation of the result of every step is also recommended. Finally, for the method presented in Table 3, the process of problem definition and searching for biological solutions is supported by a set of techniques that foster elicitation.

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<table>
<thead>
<tr>
<th>Table 1. The Bio-mimicry design method [7].</th>
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</thead>
<tbody>
<tr>
<td>Phase</td>
</tr>
<tr>
<td>1. Identification of need</td>
</tr>
<tr>
<td>2. Selection and sampling</td>
</tr>
<tr>
<td>3. Observation of the sample</td>
</tr>
<tr>
<td>4. Analogy of the natural system with the product</td>
</tr>
<tr>
<td>5. Design implementation</td>
</tr>
</tbody>
</table>

Table 2. The spiral design method [8].
In the following sub-sections, five general goals are proposed that are deemed to encompass many of the requirements pertaining to design projects for which inspiration in nature is sought. These are the basis from which a comparative analysis is drawn.

### 2.1 Goals for bionic design
The goals were selected based on their perceived level of importance and their ubiquitous relevance across design projects, albeit translated into a number of requirements, specific to the problems at hand. Communication effectiveness, form optimization, multiple requirements satisfaction, organization effectiveness and paradigm innovation for improved functional performance are the goals considered.

Effectiveness of communication depends on the sharing of a language that may be based on a code, gestures, or on signal that is appropriate to the activity and context. For effective communication to accrue it is necessary that the message is clearly delivered and received in a timely fashion, without noise, and that it is relevant to the situation or event that is ongoing.

Optimizing the shape of an object or structure can result directly from the balanced satisfaction (with concessions on both sides - trade-offs) of several key requirements, such as the reduction of material and, or, size, or the attainment of greater stability, or reduced drag, depending on the targeted objectives. It is not
always possible to achieve an optimal configuration, with maximization of all properties due to inherent conflicts that they sometimes impart (e.g. contradiction between low weight and high strength or high volume or stability). Thus, optimization requires that the configuration reached is the one that best addresses the contradictions and conflicts between the desired properties.

Compliance with multiple requirements reflects the achievement of several key points that are inherent to the problem at hand, aiming for viability and effectiveness of a small number of structures and elements that are to be used in performing more than one function. This simultaneous satisfaction opens the way for consideration of new objectives to add value to the designed product or system. Compliance with various targets, carried out by a limited set of features, structures or entities, implies seeking functional efficiency, which will result in resource savings.

Effectiveness of organization depends on the coordination of multiple structures for the performance of activities with the need of differentiation. The coordination of multiple entities in joint activity may lead to more effective results than the performance of the activity separately by each entity, such as that “the whole is greater than the sum of its parts”.

Finally, the fifth goal considered consists in achieving change in the conventional paradigm used to implement a feature, replacing it with an innovative paradigm. The latter may be proposed based on the observation of structures, behaviours and, or, processes of nature that enable improved performance of the function or feature. This is deemed to represent one of the most commonly sought goals by designers inclined to use a bionic approach.

2.2 Likelihood of achieving the goals selected by using the methods under focus

The bionic design methods at hand were subjectively analysed in terms of the support offered towards the attainment of each of the goals presented in the previous sub-section. None of the methods is deemed applicable to support the goal of effectiveness of communication, since no provisions in this regard are encompassed by any of the three.

When considering the goal of form optimization, the landscape is relatively homogeneous, with most methods deemed to offer partial support towards attaining this goal. The method of spiral design is highlighted as an exception, as it is considered particularly applicable for achieving this purpose.

With regard to satisfying multiple requirements, the analysis reveals heterogeneity across methods. While the method of bio-mimicry seems to offer no support for the pursuit of this goal, in the opposite extreme, with considerable support, is the method of bio-inspired design. In what concerns the effectiveness of organization, none of the methods analyzed is considered fully adequate to support achieving this goal.

In what concerns the innovation of paradigm for improved functional performance, all analyzed methods provide satisfactory guidelines which can support the achievement of this purpose. This suggests that the primary approach that has been recommended for bionic design is centred on functionality. Moreover, except for individual cases, the remaining goals have been given a minor importance. The results of the overall analysis are presented in Table 4.

Table 4. Perceived support of selected bionic design methods to attaining fundamental design goals.

<table>
<thead>
<tr>
<th>Bionic design method</th>
<th>Communication effectiveness</th>
<th>Form optimization</th>
<th>Multiple requirements satisfaction</th>
<th>Organization effectiveness</th>
<th>Paradigm innovation for improved functional performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bio-mimicry [7]</td>
<td>Not Applicable</td>
<td>Applicable with shortcomings</td>
<td>Not applicable</td>
<td>Applicable with shortcomings</td>
<td>Applicable</td>
</tr>
<tr>
<td>Spiral design [8]</td>
<td>Not Applicable</td>
<td>Applicable</td>
<td>Applicable with shortcomings</td>
<td>Applicable with shortcomings</td>
<td>Applicable</td>
</tr>
<tr>
<td>Bio-inspired design [9]</td>
<td>Not Applicable</td>
<td>Applicable with shortcomings</td>
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<td>Applicable</td>
</tr>
</tbody>
</table>
The bio-mimicry design method is only deemed "applicable with shortcomings" with regard to attaining the goals of optimizing form and improving effectiveness of organization. For the first goal, the assessment derives from the absence of iteration in order to pursue optimization (observing the morphological structure is what is suggested in the method that may provide limited support to pursuing this goal). For the second goal, the assessment takes into account that the method supports no direct account of organizational aspects, but only does that indirectly through structural analysis. The evaluation also results in suggesting the applicability of the method to support the pursuance of the goal of paradigm innovation for increased functional performance, and on the other hand, enables suggesting its non-applicability if the goal is to achieve satisfaction of multiple requirements and communication effectiveness.

The spiral design method was granted the rating of "Applicable with shortcomings" with respect to the goal of satisfying multiple requirements. In this method, satisfaction of multiple requirements may take place according to their explanation in the initial specification, if natural models demonstrating the reunion of the functions and, or, qualities sought are analysed. However, the method does not explicitly consider a way to guide the quest to satisfy multiple requirements. The goal of organizational effectiveness receives the same evaluation, as the aspect of organization is not considered directly in this method, but it is only implicit in the consideration of the analysis of ecosystems and natural social conditions. For the other goals at hand, this method proves to be applicable to support their attainment if the target is form optimization (especially given the nature of this iterative method, which favours systematic optimization) or innovation paradigm with regard to performance features. No support is perceived to attain the goal of communication effectiveness.

The bio-inspired design method shows gaps in the support offered to designers if the goal is to achieve optimal form, since the focus in this method is set on function. In some design processes supported by the procedures inherent to this method, the search for a biologically inspired solution to perform a given function could lead to considerations of form. However, the method does not provide procedures for optimization and does not explicitly consider form, or shape. The method is also deemed applicable in a satisfactory manner to problems where the targeted goal is either paradigm innovation for improved functional performance, or to satisfy multiple requirements, or a combination of both. However, it is not applicable to support the pursuance of the goals of effectiveness of either communication or organization.

### 3 Proposed validation approach

The analysis presented in the previous section identified goals where the methods considered were deemed to either offer no support, or only offer reduced support, towards their pursuance and attainment. Moreover, only one of the three methods (the spiral design method) entails some evaluation procedures, albeit limited in scope. This leads to suggest the integration of validation activities in bionic design processes, in order to ascertain whether the desired goals might be met by the use of the concepts generated with the support of bionic design methods. The current section presents a proposed validation approach, summarily depicted on Table 5, based on considering specific validation procedures matching each of the five goals focused in the previous section.

<table>
<thead>
<tr>
<th>Goal</th>
<th>Validation procedures to evaluate goal accomplishment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communication effectiveness</td>
<td>Validation is made according to the level of communication involved.</td>
</tr>
<tr>
<td></td>
<td>• Passive communication (triggered by observation) - the effectiveness may be evaluated by assessing the degree of the overlap between the meaning intended to be incorporated into the product or system by the designer and the readings of signification made by users or observers (empirical verification).</td>
</tr>
<tr>
<td></td>
<td>• Active communication (synchronous process between a sender and a receiver) - effectiveness evaluated from the assessment of the overlap between the messages from the sender and what is perceived by the receiver, which should conform to what is desired by the sender (empirical verification).</td>
</tr>
<tr>
<td>Form optimization</td>
<td>Validation based on a comparative approach with regard to a conventional product with functionality that is similar to the one intended for the bionic concept. Examples:</td>
</tr>
<tr>
<td></td>
<td>• Reducing material and weight - analysis from solid modeling.</td>
</tr>
</tbody>
</table>
• Stability - static analysis of mass centre (force vector modeling).
• Resistance for maximum capacity - finite element method and prototype testing.
• Object storage - capacity, maximum capacity; quantification.

Multiple requirements satisfaction
Validation based on objectively verifying, as much as possible, the level that has been reached for each property implicit in every requirement. This is followed by checking if the resolution of conflicts between non-compatible properties was made with compromises established on every side of the requirements concerned.

Organization effectiveness
Validation based on the comparison between two or more systems performing the same function (including the proposed system), but with different methods of organization. Collect measures of the levels of operation effectiveness from the (real or simulated) systems (including the proposed system), such as execution time, energy expended, material resources expended, or resources generated.

Paradigm innovation for improved functional performance
The evidence of paradigm change depends on the type of paradigm involved. Consider these examples of two kinds of paradigm change:
• Paradigm change at the organizational level - could involve changing from a centralized model of decision making to a process of cooperative decision making distributed and performed by multiple system elements.
• Paradigm change at the technical level – could involve fundamental changes in working principle, shape archetype, drive technology or kind of energy supplied.

The verification of the attainment of this goal may centre on a conceptual-analytical argument distinguishing between the existing and the new paradigm, possibly illustrated by descriptive imagery and, or, technical schemes.

4 Conclusion
The approaches to validation proposed combine engineering approaches with social science approaches to validation, in accordance with the nature of each of the goal that is focused. This validation process may necessitate further refinement and improvement, which might be attained through its use in an array of bionic design cases.

References: