Computer-Aided Biomimetics

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Abstract. The interdisciplinary character of Bio-Inspired Design (BID) has resulted in a plethora of approaches and methods that propose different types of design processes. Although sustainable, creative and complex system design processes are not mutually incompatible they do focus on different aspects of design. This research defines areas of focus for the development of computational tools to support biomimetics, technical problem solving through abstraction, transfer and application of knowledge from biological models. An overview of analysed literature is provided as well as a qualitative analysis of the main themes found in BID literature. The result is a set of recommendations for further research on Computer-Aided Biomimetics (CAB).

Keywords: Bio-Inspired Design (BID) · Biomimicry · Biomimetics · Bionics · Design theory · Innovation · Invention · Computer Aided Design (CAD)

1 Introduction

Bio-Inspired Design (BID) is associated with the application of "*nature's design principles*" to "*create solutions that help support a healthy planet*" [1]. Vandevenne (2011) added that the premise of bio-inspired design allows the finding and use of existing, optimal solutions. Additional factors include the sustainable image, association to an organism and 'high' probability of leapfrog innovations [2]. Although the technology that evolved in nature is not always ahead of man-made technology, the assumption that organisms have ways of implementing functions more efficiently and effectively than we do is assumed to be true in many cases [3, 4].

However, the search for biological systems and transfer of knowledge is non-trivial. Most Bio-Inspired Design (BID) methods use function, many in terms of the '*functional basis'* to model biological functions and flows, as the analogical connection between biology and engineering [5]. This paper identifies the insufficient definition of function throughout BID approaches as one of the main obstacles for knowledge transfer. The Biomimicry 3.8 Institute for example refers to a function as "*the role played by an organism's adaptations or behaviours that enable it to survive. Importantly, function can also refer to something you need your design solution to do*" [6].

This paper identifies the main areas of focus for research on Computer-Aided Biomimetics (CAB). Firstly, a definition of biomimetics is given that reflects its focus on technical problem-solving. Secondly, important notions from existing literature on BID are outlined based on themes for qualitative analysis. Finally, the results of the thematic analysis provide recommendations for further research on computational design tools for biomimetics.

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2 Definitions

Pahl and Beitz (2007) noted that the analysis of biological systems can lead to useful and novel technical solutions, referring to bionics and biomechanics as fields that investigate the connection between biology and technology [7]. Biomimetics is often regarded as a synonym for BID, bionics and biomimicry, and refers to the transfer of biological knowledge from nature to technical applications [8–10]. As BID is an umbrella term we adopt the following definitions, based on Fayemi et al. (2014) [11]:

Biomimetics: Interdisciplinary creative process between biology and technology, aiming to solve technospheric problems through abstraction, transfer and application of knowledge from biological models.

Biomimicry/Biomimesis: Philosophy that takes up challenges related to resilience (social, environmental and economic ones), by being inspired from living organisms, particularly on an organizational level.

Bio-inspiration can be useful in early design stages, e.g. the fuzzy front end, when the design process has no clear direction. In later stages the search for functional, biological analogies becomes less urgent and the focus lies on transferring quantitative knowledge from biological systems to technical problems. Nachtigall (2002) introduced the term technical biology as a field in biology that describes and analyses structures, procedures and principles of evolution found in nature using methodological approaches from physics and engineering sciences [12]. According to Speck et al. (2008) technical biology is the basis of many biomimetic projects. It "*allows one to understand the functioning of the biological templates in a quantitative and technologically based manner*" [13]. However, according to Julian Vincent (personal communication, March 31, 2016) technical biology has been known as biomechanics for decades.

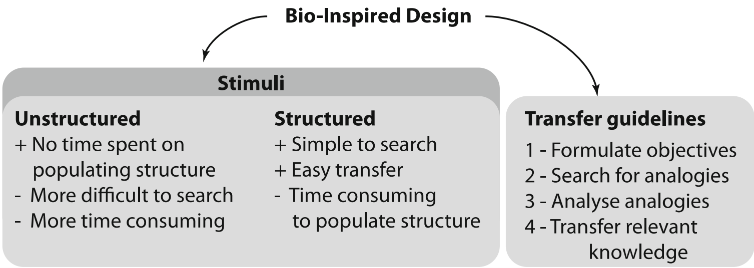

Fig. 1. Approaches of methods to 'enhance' BID (based on [5])

Martone et al. (2010) stated that, although biological models provide multifunctional properties with high potential for biomimetic applications, they have hardly been studied quantitatively in terms of their form-structure-function to transfer knowledge [14]. Figure 1 gives an overview of how methods approach BID. The next section is a literature review that aims to summarise important notions in a structure that is loosely based on seven themes for qualitative analysis. The themes represent areas that require attention in research on CAB: the transfer guidelines, the notion of function in literature and our definition of biomimetics – abstraction, transfer and application of knowledge from biological models.

3 Bio-Inspired Design Literature Review

3.1 Direction

Similar to Biomimicry 3.8, Helms et al. (2009) and Speck et al. (2008) indicated two possible directions of a biomimetics process [13, 15, 16]. The first is a problem driven, top-down process. If the knowledge of identified biological solutions is too little, Speck et al. propose an extension that involves further research on the biological system. The second is a solution driven, bottom-up process that searches for technical applications of a specific biological solution. Main characteristics are [13]:

Bottom-up (biological solution to technical problem)

- Abstraction often proves to be one of the most important as well as difficult steps
- Often several iterative loops
- 3–7 years for bottom-up to final product
- Possibly multiple implications of technology
- Potentially highly inventive

Top-down (technical problem to biomimetics)

- Existing product: Initially define problem and constraints, then search for possible biological solutions
- One or two most appropriate selected for further analysis
- 6–18 months top-down to functional prototype
- Usually not very innovative

Extended top-down

- Existing knowledge of biological model is too low, further research is required
- Can be as highly inventive as bottom-up
- Smaller range of implications of technology compared to bottom-up
- 1–5 years typically, in between top-down and bottom-up

Helms et al. (2009) noted that the steps in these processes in practice do not necessarily occur in the prescribed sequence. Once a biological solution is selected in the problem-driven process, the design process tends to be fixated around this one solution.

Furthermore, they identified several common errors and practice patterns that emerged during classroom projects on bio-inspired design [15]. Both are listed in Table 1.

3.2 Formulate Objectives

Lindemann et al. (2004), Stricker (2006), Inkermann et al. (2011) proposed a procedure that starts with a goal definition, based on the the Müncher Vorgehensmodell (MVM) by Lindemann (2003) [17–20]. The goal, as well as the later search for alternative solutions, are at a relatively abstract level. Stricker (2006) identified several problems during BID processes listed in Table 1 [18].

By our definition, the goal in biomimetics is solving technical problems. Stricker (2006) noted that knowing the type of problem you are dealing with, helps planning a solution route (based on Dorner 1987, Badke-Schaub et al. 2004, Erlenspiel 2003) [18]:

Table 1. Mistakes and trends that often occur during a bio-inspired design process (based on [15, 18]).

Stricker (2006) errors	*Helms et al. (2009) errors*	*Helms et al. (2009) trends*
• Over-reduction of context • Neglecting form and processes by focusing mainly on structure • Generalising where different functions originate and simply copying existing foreknowledge • Structure is expected to be directly transferable (same elements, same relations) • Neglecting of constraints	• Vaguely defined problems • Poor problem-solution pairing • Oversimplification of complex functions • Using 'off-the-shelf' biological solutions • Simplification of optimisation problems • Solution fixation • Misapplied analogy • Improper analogical transfer	• Mixing problem-driven versus solution-driven approach • Usually focus on structure instead of function • The focus on function, usually problem-driven • Solution-driven generated multi-functional designs • Partial problem definition leads to compound solutions for new-found sub-problems. • Not many problems are framed as optimisation problems • Tendency to choose known biological solutions • Choice of biological solutions hard, too many or not enough

Synthesis barrier: goal is known, but the means to achieve it are not known
Dialectical barrier: goal is not known, ambiguous, multi-faceted, interrelated or too generic
Synthesis and dialectical barrier: combination of above, but knowledge not sufficient
Interpolation problem: means and goal known, but not clear how to achieve the goal

In BID both problem and solution decompositions are transferred [21, 22]. "*BID often involves compound analogies, entailing intricate interaction between problem decomposition and analogical reasoning*" [21].

3.3 Search for Analogies

Analogies in BID can be useful for solution generation, design analysis and explanation [5, 10]. To validate applicability of analogies through similarity, Inkermann et al. (2011) distinguish four types of similarities [19]:

Formal similarity: same rules and physical principles
Functional similarity: similar function
Structural similarity: similar structural design
Iconic similarity: similar form or shape

Databases are a common approach to store biological analogies, usually indexed by function. According to Yen et al. "*a designer can compare the functions of what they are designing and also compare the structures and behaviours of their design to biological systems*" [23]. Hill (1997) classified 191 biological systems into 15 descriptive technical and biological abstractions on basis of 5 general functions and 3 types of transactions: energy, information and matter [18, 20]. DANE, SAPPhIRE and the more recent Biologue system are databases indexed using the Structure-Behaviour-Function (SBF) model [23–25]. Wilson et al. (2008, 2009) and Liu et al. (2010) used an ontology based knowledge modelling approach to reuse strategies for design [26–28].

Natural language approaches are another way to search for relevant biological analogies. Shu et al. (2014) proposed a semi-automatic search method using functional keywords [2, 29]. According to Vandevenne (2011) these studies indicate that representation of analogues in natural language format should be considered as input for filtering, analysis and transfer. "*Automated characterization of biological strategies, and of the involved organisms, enables a scalable search over large databases*" [2].

Yen et al. (2014) noted that the search strategy for biological systems is a problem area. To make the search process more efficient, Vandevenne (2011) proposed searching on basis of function and further specification of behaviour and structure before commencing knowledge transfer. Other areas that require attention are methods for teaching analogical mapping, evaluating good analogies, good designs and good design problems [23].

An example of research on better understanding and supporting the use of biological analogies is the work by Linsey et al. (2014). According to them design by analogy is powerful, but a difficult cognitive process. To overcome cognitive bias and challenges they propose several principles and design heuristics. An example is providing uncommon examples to overcome design fixation [30]. The use of analogies and heuristics may be useful for biological inspiration and even supporting transfer of knowledge. However, "*databases can only record history and cannot deduce new relationships*" [31]. Therefore, Vincent (2002, 2006, 2009) proposes the use of TRIZ to facilitate the comprehension of biological systems [8, 9, 32]. Lindemann et al.

Gramann (2004) provide a structured, associative checklist to support deduction of technical analogies from biological systems that is loosely based on TRIZ [17]. Vincent et al. developed BioTRIZ, a reduced form of TRIZ that inventive principles to biological dialectical problems [8, 33]. "*Studying 5,000 examples, the conflict matrix was reduced from 39 conflict elements to 6 elements that appear in both biology and engineering, and a 6 by 6 contradiction matrix that contains all 40 of the inventive principles was created. These 6 conflict elements are substance, structure, time, space, energy/field, and information/regulation*" [5].

3.4 Function

Fratzl (2007) noted biomimetics studies start with the study of structure-function relationships in biology; the mere observation of nature is not sufficient [34]. Vincent (2014) noted defining problems in functions is key to knowledge transfer from biology to technology [4]. According to Stone et al. (2014) natural systems have to be modelled using normal function modelling techniques to use function as an analogical connection [5]. An example is using the functional basis that defines function as "*a description of a device or artefact, expressed as the active verb of the sub-function*" [35]. However, Deng (2002) identified two types of functions in literature [36]:

Purpose function: is a description of the designer's intention or the purpose of a design (not operation oriented).
Action function: is an abstraction of intended and useful behaviour that an artefact exhibits (operation oriented).

Furthermore, Deng (2002) stated that action functions can be described semantically or syntactically. Chakrabarti et al. (2005) adopted this view, an overview of definitions is given in Table 2. For SAPPhIRE Chakrabarti et al. (2005) view function as "*the intended effect of a system (Chakrabarti & Bligh, 1993) and behaviour as the link between function and structure defined at a given level. Thus, what is behaviour is specific to the levels at which the function and structure of a device are defined*" [25].

Table 2. Action functions from the perspective of semantic and syntactic formulation - based on [25, 36].

Semantic views	***Syntactic views***
Functions as input/output of energy, material and information	Functions using informal representation (e.g. verb-noun transformation)
Functions as a change of state of an object or system.	Functions using formal representation (e.g. mathematical transformation).

Nagel (2014) used a semantic view and noted that a function represents an operation performed on a flow of material, signal or energy [37]. According to Nagel (2014) the use of functional design methods for BID offers several advantages [38]:

- archival and transmittal of design information
- reduces fixation on aesthetic features or a particular physical solution
- allows one to define the scope or boundary of the design problem as broad or narrow as necessary
- encourages one to draw upon experience and knowledge stored in a
- database or through creative methods during concept generation

Vattam et al. (2010) adopted the formal definition for function used in Structure-Behaviour-Function (SBF) models, which was developed in AI research on design to support automated, analogical design [24]. This is a semantic view on functions for SBF: "*A function is represented as a schema that specifies its pre-conditions and its post-conditions*" [39].

Goel (2015) noted that BID presents a challenge for Artificial Intelligence (AI) fields such as knowledge representation, knowledge acquisition, memory, learning, problem solving, design, analogy and creativity [40]. Vandevenne (2011) noted that the instantiation of functional models is a labour-intensive task that requires biology and engineering knowledge [2].

3.5 Abstraction

Abstraction, the reduction of context, is an important aspect in all BID methodologies. According to Vattam et al. (2010) successful BID requires rich and multimodal representations representations of systems during design. Such representations are organised at different levels of abstraction. They "*explicitly capture functions and mechanisms that achieve those functions on the one hand, and the affordances and constraints posed by the physical structures for enabling the said mechanisms on the other hand*" [41]. Table 3 is an adaption of the lists by Fayemi et al. (2014) on requirements for abstraction from both a theoretical and a practical perspective.

Table 3. Requirements for abstraction - based on [11]

Theoretical	*Practical*

• Ability to model simple as well as complex problems
  o Integrate different systemic levels
• Effective selection of significant data
  o Maintain specific constraints of problem
• Ease of translation
  o Determine the solution in generics terms
	• Fast process
	• Intuitive process
	• Allow combination with other tools
	• Applicable over various industrial/scientific domains
	• Allow for collaborative design

Abstraction eases the implementation of biological solutions [4, 20]. Chakrabarti (2014) found that exploration at higher levels of abstraction has a greater impact on novelty of solutions generated [22]. Lindemann et al. (2004) noted that, if one finds no technical analogies, the level of abstraction as well as the feasibility of solving the problem should be reconsidered [17].

Diagrammatic representations of biological systems lead to generation of more and better design ideas than textual representations [42]. Descriptive accounts of design lead to more effective educational techniques and computational tools for supporting design, advantages include: realism, accuracy of predictions and accuracy of design behaviour [15].

3.6 Transfer

In order to deduce new relationships, Vincent (2014) suggested using a descriptive approach of technology to ease knowledge transfer. "*There is very little indication of how one can take a concept from its biological context and transfer it to an engineering or technical context*" [31]. Differences in context, high complexity, high amount of interrelated and integrated multifunctional elements make transfer the most difficult part of BID. Lack of biological training increases the difficulty of transferring knowledge. Chakrabarti (2014) defined transfer as "*the reproduction of information from a model of a biological system in a model or prototype for a technical system*" [22]. There are four kinds of exchanges in bio-inspiration [22, 42]:

1. Use of analogy as idea stimulus
2. Exchange of structures, forms, materials
3. Exchange of functions, and processes
4. Exchange of knowledge about processes, information, chaos

With the aim of initiating work in systematic biomimetics Chakrabarti et al. (2005) developed a generic model for representing causality of natural and artificial systems [25, 42]. Using this model they analysed existing entries of biological systems and corresponding technical implementations based on similarities and identified several mechanisms of transfer [42]. Only the transfer of physical effects and the transfer of state changes of processes were however considered.

Vandevenne (2011) notes that DANE forces designers to understand the systems of candidate biological strategies in detail, as well as the obtained abstraction. This facilitates knowledge transfer and communication [2].

3.7 Application

Helms et al. (2010) sketched a macro-cognitive information processing model of BID to support the development of computational tools that support this form of design. They noted the complex interplay between problem definition and analogy mapping for knowledge transfer. Salgueiredo (2013) applied C-K theory to BID in early design phases and showed that biological knowledge is usually implemented once the traditional path is blocked. In this case the acquisition of biological knowledge is required to find 'unexpected properties'. She noted that the systematic implementation of BID in companies requires a different form of knowledge management. In essence, C-K theory is a theory of design knowledge management [10, 43]:

- The theory captures the iterative expansion of knowledge and enrichment of design concepts.
- Concept-space can only be partitioned into restrictive and/or expanding.
- partitions, relating to constraints to existing knowledge and addition of new knowledge.
- The theory is domain-independent, which is useful in supporting/analysing multi-disciplinary design.

These findings are in line with the co-evolution of problems and solutions mentioned by Chakrabarti (2014) and the generation of compound solutions through iterative analogy and problem decomposition mentioned by Vattam et al. (2010) [22, 24]. Salgueiredo (2013) concludes that "*biological knowledge does not offer solutions, it stimulates the reorganization of knowledge bases, creating bridges between different domains inside the traditional knowledge. This conclusion is important for reducing the risks of idolizing nature processes and systems*" [10].

4 Results Thematic Analysis

Based on the seven themes 40 features were identified that are of interest for CAB. These features repeatedly occurred in the literature described in the previous section. 190 relationships between them were documented. Relationships were weighted with factor 1, 3 or 5, based on their relative importance. Relations weighted with factor 3 or 5 were annotated. Figure 2 shows a selection of visualisations, features are represented as nodes and relationships between them as edges. In the software package Gephi a radial axis layout was used to create these visualisations, which supports qualitative analysis of similarity for the determination of main themes [44, 45]. As one might expect, nodes like *Transfer* and *Analogy* are highly inter-connected with the network. Less expected are *Holistic approach, Validation* and *Confusion of terms*. Other factors of interest are *Transfer-impediment*, *For computational purposes* and the differences in the sub-groups of abstraction. The annotated edges were used to determine feature influence and overlap. Main areas of focus we found and specific points of attention are:

- Holistic approach
  - Iteratively improve problem/goal and expand knowledge supports validation
  - Alternating problem-driven and solution-driven approach
  - Attention to heuristics and principles, e.g. [30]
  - Attention to macro-cognitive model, e.g. [21, 24]
- Abstraction
  - Abstraction should maintain relevant constraints and affordances
  - Use various levels of abstraction for complexity and multi-functional problems
  - Attention to problem definition and problem types
  - Attention to validation of abstracted entries in knowledge base
- Analogies
  - Representation of relevant knowledge for transfer
  - Attention to analogy mapping and analogical reasoning
  - Attention to analogy representation: natural language (descriptive), diagrams

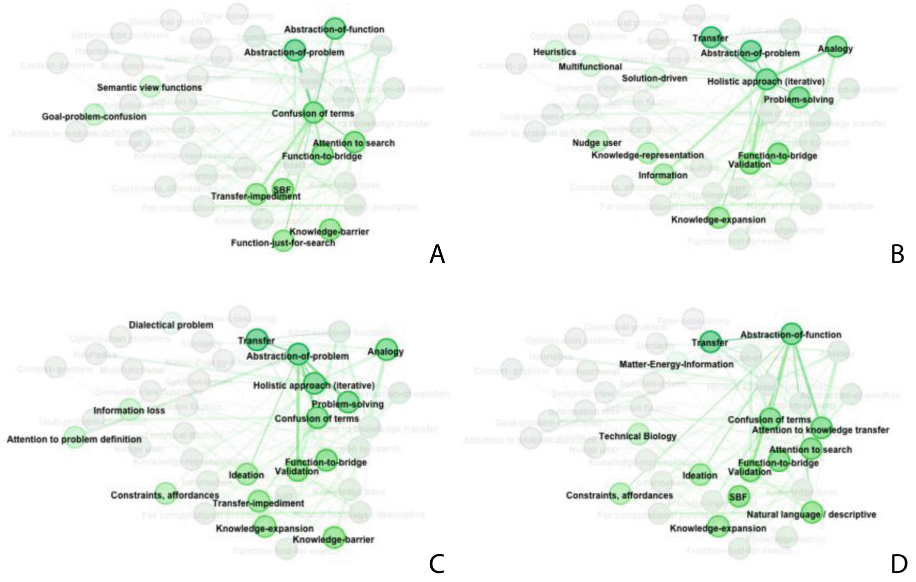

Fig. 2. Visualisations of features and relationships found during thematic analysis. The groups display a selected node and their most influential neighbours. The highlighted nodes in A-D are in alphabetical order: *Confusion of terms, Holistic approach, Abstraction of problem, Abstraction of function.*

- Confusion of terms and computational approach
  - Function is key and needs accurate definition for:
    - Problem decomposition
    - Wrong interpretation of interrelated terms (SBF)
    - Improve search for analogies and transfer
  - Automated characterisation improves scalability of knowledge base
- Transfer (impediments) and validation
  - Descriptive biological knowledge support realism and accuracy
  - Attention to supporting possible lack of biological knowledge
  - Attention to validation of analogies, e.g. through similarity

5 Discussion and Outlook

Some attention points for Computer Aided Biomimetics (CAB) were briefly introduced in the previous section. These are derived from a simplified qualitative analysis of the literature addressed in Sect. 3. The focus during analysis was on finding generic guidelines for the development of computational tools that support a BID process. The usefulness of these findings is left to the reader to decide.

In general, more attention should be paid to definitions, constraints and affordances, optimisation problems, the holistic approach and the validation mechanism. Validation for example is only possible when the required, relevant knowledge is accessible. However, the extended process described by Speck et al. (2008) implies that knowledge expansion drastically affects development time [13]. Investing additional time may not be desirable and Salgueiredo (2013) is right in concluding that BID should not be idolised [10].

BioTRIZ has, based on a non-systematic review of the literature on biological processes, changed the usual classification into '*matter, energy and information*' to '*substance, structure, time, space, energy/field, and information/regulation*' to allow better abstraction of biological phenomena. Further research is to aim at using TRIZ tools for CAB and Inventive Design [46] in cooperation with Julian Vincent and Denis Cavallucci.

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