

BREED - A Problem Solving Bionic Design Methodology

Rohith Vaidyanathan ¹, Gururaj Fattepur ² and Ravi C Guttal* ²
rohithvaidya@gmail.com ¹, gururaj_f@kletech.ac.in ², ravi_g@kletech.ac.in ²

¹ Center for Innovation and Product Development, School of Computer Science and Engineering, KLE Technological University, Hubli, India

² Center for Innovation and Product Development, School of Mechanical Engineering, KLE Technological University, Hubli, India

*Corresponding Author: ravi_g@kletech.ac.in

Abstract

Bionic designs which have evolved from time-tested strategies of nature have been a source of inspiration for designers to solve problems. Current bionic design methods are analogical and hence are discordant to the design engineering workflow. A methodology is proposed which suggests suitable bionic forms to a given design space. The methodology consists of the following stages which are **B**ionic representation, **R**elation, **E**mulation, **E**ngineering specifications, **D**esign verification and optimisation (BREED) and finally realisation. This methodology aims to function as a systematic problem-solving approach to retrieve structural inspirations from nature and mimic its form. Inspiration and validation phases of the bionic structure are represented as a V-model. The designer can leverage this framework to come up with novel bionic design concepts.

Keywords

Biomimicry, Computer Aided Design, Design Automation, Design methodology, Engineering design

Introduction

Bionic designs hold a lot of intrigue and potential because they have been developed by the process of natural selection over millions of years. Nature's forms have been one of the sources a designer seeks to emulate because of its inherent efficiency or its aesthetics. Mimicking Bionic forms can also be viewed as a paradigm for sustainability (Pauw, 2010). Natural selection is driven by mutations which are favourable for survival of the organism in a particular environment. Accumulation and combination of mutations yield great diversity with time. Thus over 10 million species are estimated to exist on Earth (Ayala, 2007).

Databases/Tools with biological information have been developed to give engineers and product designers better access to inspirations from nature (Chakrabarti, 2017; Deldin, 2014; Siddharth, 2017). However, bionic innovations continue to be cognitive and empirical in nature (Coelho, 2011). Exhaustive experimentation is required to meet design targets (Fu, 2014). The vast diversity in species also makes it harder for designers to explore nature's concepts. Designers' reluctance to use structured design methods point towards the need for computational methods or automation of design processes (Chakrabarti, 2011). Hence, the key to successfully incorporate bio-design in mainstream industrial products is to develop tools, methodologies and guidelines which aid designers who lack profound biological knowledge. Amaresh et al. conclude that although analogical design methods (Colombo, 2008; Lopez, 2012; Rossin, 2010; Shu, 2010) have achieved great strides in database retrieval, adaptation by engineers and designers remains a challenge. Engineers work with a well-defined plan having a vision on what has to be produced with available technologies (Helms, 2009). They select requisite materials, manufacture and assemble them according to a process to make sure that the required function is achieved. However, biological entities develop capabilities as an adaptation to the environment. But, biological design knowledge is metaphorical which does not suit the workflow of engineers. The bio-inspired design process is not complete just by choosing the right living prototype (Vincent, 2006); it must fit the given engineering context as well. Bionic design, therefore, requires methodologies which incorporate validation and are

goal-oriented to achieve the design target rather than a case by case analogy (Maier, 2011). Design research must support the industry by improving the understanding of the engineering design process (Blessing, 2009). Hence, the outcome of the design methodology must be manufacturable, satisfy the objectives of the design and fit the constraints of the situation. The advent of additive manufacturing offers new design possibilities and has added advantages over traditional manufacturing processes.

Biomimetic design methodologies can be classified broadly into problem-driven or solution-driven approaches (Lenau, 2018). Solution driven bionic design follows a top-down approach searching for applications after identifying the biological strategy. Problem driven bionic design (Vincent, 2006; Maier, 2011; Baldussu, 2015; Yu, 2019) alternatively searches for biological inspirations to a given engineering problem. Although, problem-driven design is systematic the current methods do not address the contextual fit of a biological design to an engineering design problem. One such example is the Product Design from Nature methodology (PDN) proposed by Hui-I Wen et al (2008). The omission of design validation by Hui-I Wen et al. (2008) creates a void in the product design and development process. Du Plessis et al. (2019) add simulation-driven design and lattice design to the list of bionic methodologies. However, designs obtained from topology optimisation and simulation-driven design are sometimes termed as bionic/bio-mimicked. Although the designs show convoluted forms, terming them bionic is inaccurate since they have no specific biological input. It is also otherwise true that outputs from these design processes can lead to solutions found in nature unexpectedly. Hence, these computational design processes can serve as a bridge to fit a bio-design to an engineering context. A retrieval mechanism along with simulation to validate the retrieved bionic input could lead to more realistic designs, which can be used for real-life applications. An analytical methodology can be easily adopted by engineers in their workflow. It will lead to practical implementations rather than conjectural design innovations.

This paper proposes the BREED methodology, a systematic approach which starts with recommending a bionic form for a design space, validate and optimise the design to obtain a bio-inspired structure. This methodology is demonstrated using case studies which elucidate the steps proposed in the framework.

1. BREED Methodology

BREED is a methodology to mimic bionic forms for a given design space. It follows a V-model as depicted in Figure 1. The methodology uses inspire and validate constructs. The first half of the V represents the inspiration phase. Inspirations from nature for a design space are obtained in this phase. Biological inputs obtained from the inspiration phase are fit to the engineering context through geometric modifications and material selection by the designer. The second half represents the validation phase which consists of verification and optimisation of the inspired form. The methodology culminates with realisation of the structural design.

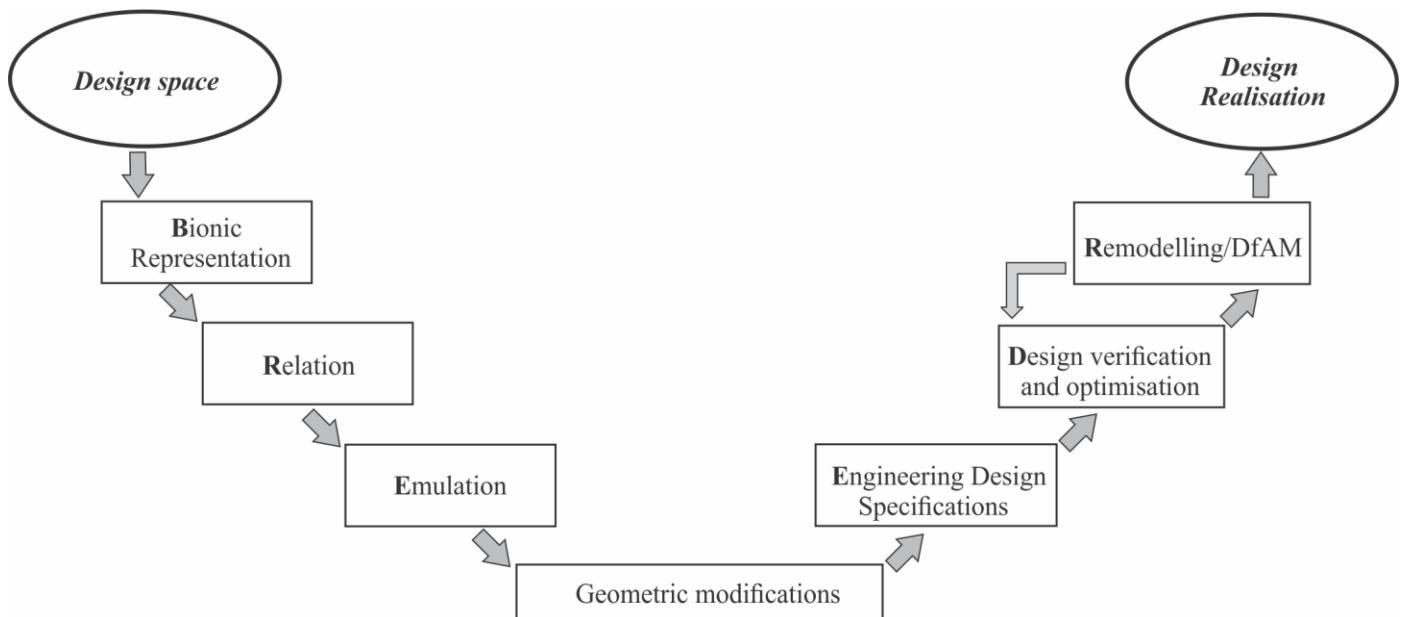


Figure 1 : BREED Methodology for Bionic design

The objective of the framework is to give the designer/engineer a reliable tool to search for structural forms in nature which match the design space. A good match between bionic form and the design space ensures similar structural performance and behaviour. Stability, strength, durability and vibrations are some of the key objectives of structural design.

A design problem does not have a unique solution (Maier, 2011). The methodology allows the designer to remodel the bionic structure, to accommodate support structures, features for engaging with secondary structures, manufacturability constructs and aesthetic appeal. The design validation and optimisation stage also involves remodelling iteratively to meet the design targets. The structure may be remodelled before the manufacturing stage to ensure efficient and cost-effective realisation.

1.1 Inspiration phase

A plethora of interesting optimal and robust structures prevail in nature. Mimicking these structures requires an accurate representation of the form. In the inspiration phase, engineers/designers can arrive at a suitable bionic form which closely represents the design space. This follows three stages (**B**ionic representation, **R**elation and **E**mulation) to attain a bionic form for the structure.

Bionic representation stage defines how bionic forms are stored in the BREED database. Figure 2 shows some methods by which bionic forms can be represented in the database. Relationship between models, retrieval and search depend on the mode of representation. The type and amount of data will also determine the selection of a suitable configuration for the bionic database. An analytical representation of the bionic form and design space is needed to derive key attributes. Some of the examples are structured or unstructured point sets (which require statistical representation also called templates), Discretisation, surface-edge-vertex models, generalised cylinder models etc. The representation of models must establish the uniqueness between them. Intricacies between curvatures, contours, point sets etc. must be considered in this stage. The designer will be able to query the database once the association is established.

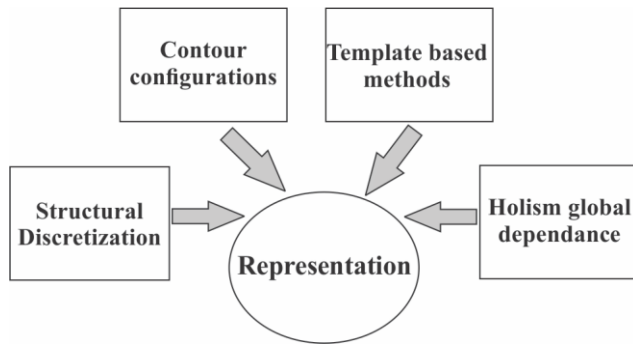


Figure 2 : Representation methods for a design space

Relations such as aspect ratios can be used to classify a design space. For example, $l \gg b$ could be a feature of the design space. As geometries get complex, more relations are needed to describe the structure (Kazhdan, 2004). Sir d'Arcy Thompson (1915) showed that the outlines of two hatchet fish of different genus, *Argyropelecus olfersi* and *Sternoptyx diaphana*, can be transformed into each other by shear and scaling. Hence a relation by affine transformations can be used to differentiate between the two genus of the hatchet fish. Other methods for relation are shown in Figure 3.

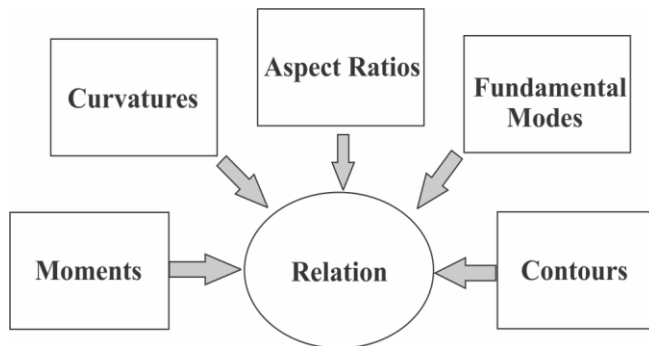


Figure 3 : Methods for relation

Emulation: A suitable metric must be able to analytically capture the relationship defined in the previous phase. Derived relations suggest the proximity of the design space to the bionic representation. Similarity measures must capture the essential properties (Kazhdan, 2004; Veltkamp, 2001). A discrete metric can be used for affine invariant relations. The designer can establish the closeness between different bionic models in the database. Figure 4 shows some of the common distance metrics. Thus, the designer will have an array of bio-design inspirations which can be considered for the design space.

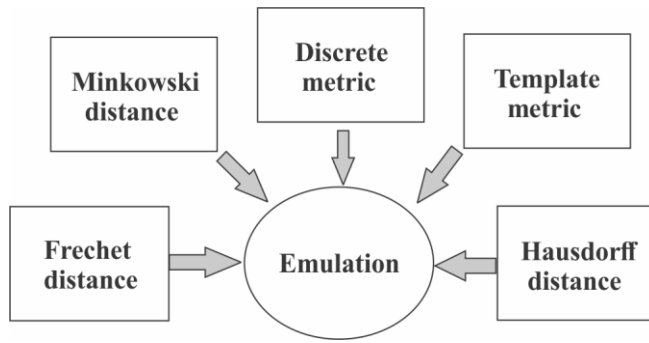


Figure 4 : Emulation metrics for form comparison

1.2 Validation phase

A bionic structure obtained from nature cannot be directly mimicked. Engineering constraints play a vital role in determining the fit to the problem. The mimicked form must meet certain engineering design goals for successful realisation, hence designers/engineers must consider essential engineering attributes for adoption of the bionic form. It is also necessary that the structural form be validated based on engineering specifications and business objectives.

Geometric Modifications

Geometric modifications may be essential to incorporate boundary conditions (both displacement and load) for the structure. To satisfy functional requirements and aesthetics, further modifications to the bionic form may be required.

Engineering specifications

The specifications evolve from customer needs, functional requirements, standards and homologation norms. Engineering and functional specifications are essential inputs from the designer. Engineering design is posed as a multi-objective optimisation problem with several objectives and constraints which translate into engineering specifications. These specifications govern the alternatives that are best suited to solve the design problem.

Design Verification and Optimisation

Virtual prototyping and physical prototyping are cornerstones of the design verification and validation process. This step verifies and validates the design to meet all vital engineering specifications and customer needs. Virtual prototyping has obvious advantages in terms of time and cost efficiencies. Virtual prototyping also facilitates efficient iterative design optimisation processes. This step also includes remodelling especially when the design fails to meet the specifications.

Design optimisation is typically performed in conjunction with verification and validation step. The design can be optimised by modification of its topology or its design parameters. The designer according to the context, can set the objectives for optimisation.

Microstructures or lattices can also be used by designers to further explore optimisation options. R. B. Lippert et al. (2016) use design infills for optimisation of structures. The homogeneity of macrostructures is altered by various lattices with bionic origin. The infills are validated and optimised using finite element methods to achieve specific objectives.

2. Conclusion

Adaptation of bionic form to a structural engineering design space requires problem-solving methods, which arrive at a bionic inspiration for the problem, rather than analogical methods. Furthermore, methods need to address the context of the engineering problem to integrate the retrieved biological input. This ensures the realisation of the bionic design innovation. The BREED methodology proposed for structural biomimicry follows the inspiration and validation phases. The methodology encapsulates vital aspects of design to ensure that the output is not just a concept but an implementable design solution. In this work, a procedure has been defined based on the methodology which uses shape context similarity, simulation and optimisation techniques to achieve the design target. Development of such procedures can lead to computational tools which aid the bionic design process. The engineer/designer need not have biological knowledge or awareness to obtain inspirations from nature. New procedures based on the methodology can be developed based on the type and size of biological data available and existing procedures modified to improve scalability and speed. However, procedures do not completely replace the inputs of the designer. Human inputs are vital to address the influential factors of the

design. Hence, it is necessary for the software/tool to give leeway for human intervention. The case study of the structural dome clearly illustrates how a bionic form in nature (mushroom crown) which closely resembles the given design space can be incorporated. Additive manufacturing is an enabler for realising intricate structures emanating from the BREED methodology. Design for Additive Manufacturing (DfAM) is needed to accommodate the constraints of the machine and process of AM. The potential of biomimicry can only be highlighted by successful implementation of bionic products in the industry.

The BREED methodology can be extended to other aspects of biomimicry like materials, mechanisms and processes in nature. Furthermore, recursive implementation of BREED can effectuate multi-level optimization of engineering structures using various design paradigms.

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