BREED - A Problem Solving Bionic Design Methodology

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Bionic designs which have evolved from time-tested strategies of nature have been a source of inspiration for designers to solve problems. The beauty of nature's form is derived from effective evolution and robustness of its function. Current bionic design methods are analogical and hence are discordant to the design engineering workflow. In this paper, a methodology is proposed which suggests suitable bionic structures 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 realization. This methodology aims to function as a systematic problem-solving approach to retrieve structural inspirations from nature and mimic its form. The methodology also integrates biological inputs to the context of an engineering design problem. 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. A structural dome is used as a case study to demonstrate the procedure of BREED methodology. Biological forms for the dome are obtained using a spectral matching technique. The bionic design is validated after applying relevant boundary conditions and by using proven engineering methods.

Keywords: *Design methodology, Biomimicry, Design optimisation, Structural Design, Product Design*

1. 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.

2. 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

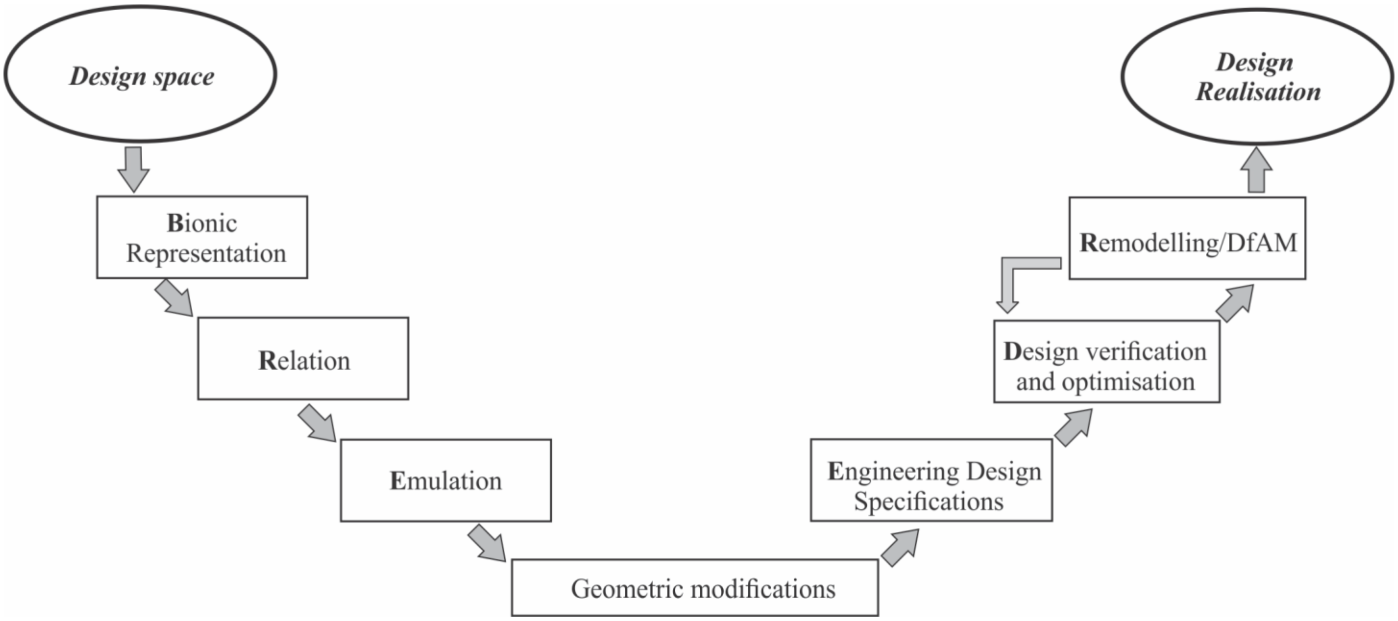

Figure 1 : BREED Methodology for Bionic design

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.

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.

2.1 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.

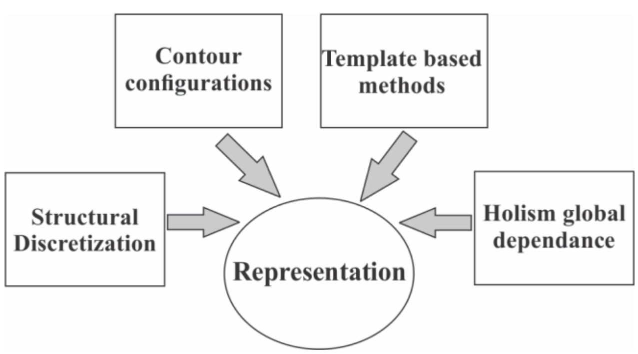

Figure 2 : Representation methods for a design space

Relations such as aspect ratios can be used to classify a design space. For example, l>>>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.

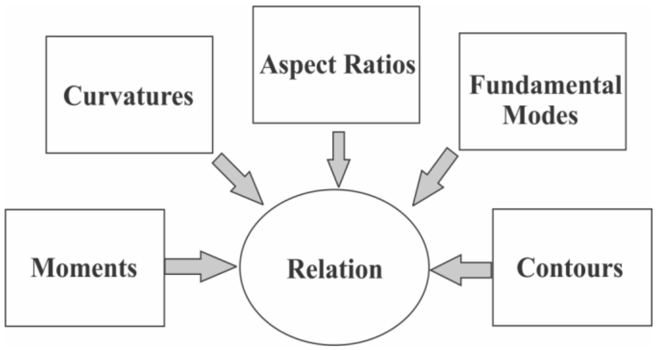

Figure 3 : Methods for relation

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.

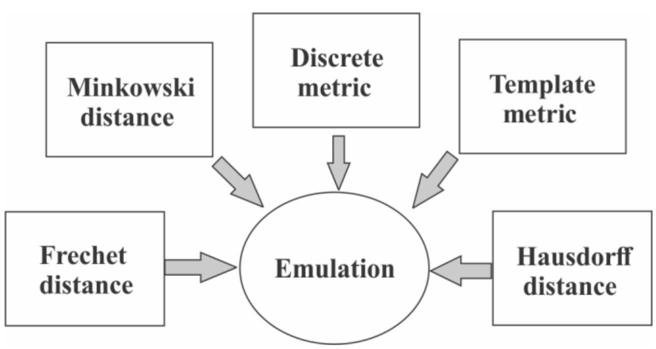

Figure 4 : Emulation metrics for form comparison

2.2 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 it's 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.

2.3 Realisation

Any design proves its success by its capability to be prototyped and manufactured. Thus, choosing the right manufacturing technique is critical to realise the design. Many manufacturing techniques have been enlisted to fabricate structures using casting, forming, moulding, bending and material removal techniques such as machining. Care has to be taken to select the proper technique as it decides the ease and efficiency of manufacturing. A major challenge encountered in bionic structures' realisation is the efficiency at which they can be manufactured.

3. Procedure based on BREED methodology

Procedure is defined as a series of actions conducted in a certain order to achieve a goal. Figure 6 depicts a procedure using the BREED methodology. The procedure uses the inspiration and validation phases of the methodology to arrive at a design solution. Similar procedures can be developed based on the type of database available and selection of techniques and algorithms. For this example, the procedure uses a bionic database of 3D discretised models. The discretised entities associated by Eigenmodes are compared by the cloud to mesh (C2M) distances.

Procedures lay down the foundation for computational design and automation. Computational tools/methods have been developed based on these procedures. Different procedures of BREED methodology are possible depending on available datasets and relationships between data points.

3.1 Bionic Representation - Discretised models

The procedure developed uses discretised 3D models for the representation stage. Stems of banana trees, bamboos, water lilies, tree branches etc. are some of the structures available in nature that represent the form of a beam. *Bambusa* bamboos which are native to Southeast Asia, have a cylindrical layer of tissues that form a tubular structure. The tubular shape minimises stresses, but equally important is that it also maximises flexural rigidity (Schulgasser, 1992). The discretisation must capture the intricacies of the bionic form which can then be used for comparison.

3.2 Relation - Principal features of the design space

Structural forms in nature which have superior functionality must be characterised in an analogous fashion to the engineering design space. Hence, structures similar in the macro form need to be suggested to the designer. The relation must capture the salient strength and functional features of the structural form. Hence, Eigenmodes are chosen to characterise bionic forms and the design space. The mode shapes are represented by the eigenvectors of the form. The mode shapes and frequencies are obtained by the third invariant given by equation (1),

$$\det([K] - \omega^2\,[M]) = 0 \qquad (1)$$

Where, K is stiffness tensor, M is mass tensor

At discrete eigenvalues (ω_i), the third invariant (det) becomes zero. Hence, the eigenvector (φ_i) derived from equation (2),

$$[K - \omega_i^2 M]\{\varphi\} = 0 \qquad i = 1, 2, 3 \ldots. \qquad (2)$$

Eigenmodes act as unique signatures of the structure. Consistent physical and material properties are chosen for both the design space and the bionic forms. Therefore, contextual structures exhibit similar Eigenmodes which means that the bionic structure in the database can be mimicked to the design space. The first 3 non-zero Eigenmodes with high wavelength are chosen to represent the structural form.

3.3 Emulation - Shape context comparison

The bionic forms are stored in the database as discretised models. The distance (a metric for geometric matching) between the fundamental modes of the bionic form and the design space will determine whether the bionic form can be mimicked or not. The mode shapes of the design space are converted to a point cloud and compared to the corresponding mode shapes of the bionic forms. Structures in nature need not always show the same dimensional properties but can be similar in form. Scale invariance is a factor that must be considered when bionic forms need to be mimicked (Fish, 2009). Therefore the mode shapes are converted to the same scale by determining the maximum bounding box dimension. Iterative closest point (ICP) method is used to align the models in comparison. A transformation is applied to the bionic structure with the design space as a reference. The alignment is done ensuring maximum overlap. Cloud to Mesh (C2M) distance algorithm is used to compare the mode shapes. The orthogonal distance from the point in the cloud to the nearest triangular element is computed. If the orthogonal distance, does not fall in the triangle, the shortest distance to one of the edges of the triangle is taken. Similarly, distances from all the points are computed (Jones, 1995). This method can also be used to query bionic forms from existing structural bionic databases.

The similarity of the bionic form to the design space is determined from the histogram of the calculated distances. The histograms are compared by the Mode of the data. Mode represents the highest data peak. Based on this score, the system shall suggest the bionic forms which can be mimicked to the design space.

3.4 Engineering specification and Design optimisation

The mimicked bionic form must be modified to match the engineering use case. Engineering specifications shall be specified based on the context and customer requirements. Load cases for the structure and material inputs are specified to perform structural analysis. Objective functions are derived from engineering specifications and may include minimising/maximising mass, strength, stresses induced, Eigen frequencies etc. The design form is further optimised using topology optimisation or generative methods (Yu, 2019; Mccormack, 2004). After remodelling by the designer with aesthetic intent, an optimal, validated structure is sent for manufacturing.

3.5 Realisation - Additive manufacturing

The success of a methodology depends on the practicality of its result. The optimised structure from the validation stage must be manufactured to complete the design process. Manufacturing of complex and intricate geometries is possible by the process of additive manufacturing (AM). It also augments the ongoing search for weight improvements in several industries (Emmelmann, 2011(a)). Additive manufacturing gives design freedom as it can print structures that were not possible due to constraints of conventional manufacturing. However, process and machine constraints have to be considered, especially while printing infill structures (Emmelmann, 2011(b)). Techniques of AM include Material Jetting, Binder Jetting, Material Extrusion, Powder Bed Fusion, Sheet Lamination, Directed Energy Deposition and Photopolymerisation. Among these, Material Extrusion or Fused Deposition Method (FDM) is the most widely and commercially used additive manufacturing process for fabricating prototypes and functional parts. It uses a thermoplastic filament which, when heated to its melting point temperature, can be deposited to create a three-dimensional object. FDM technique has been considered in the realisation phase of this procedure. The bionic form which meets the imposed design targets shall be sent for manufacturing. Design for additive manufacturing plays an important role and is incorporated in the procedure of the BREED methodology. Figure 5 shows the intermediary factors in the design for additive manufacturing.

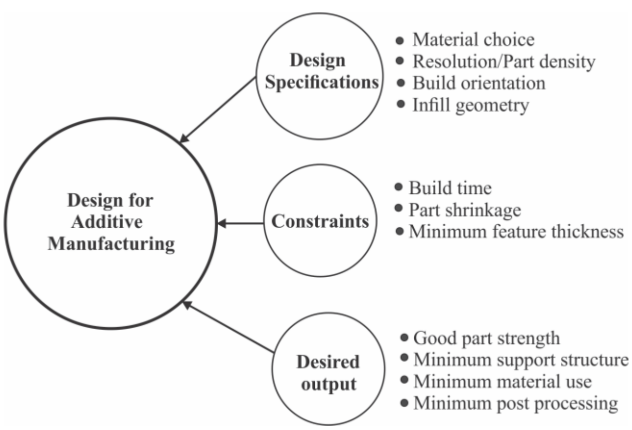

Figure 5 : Factors to be considered for additive manufacturing

Minimum wall thickness

Wall thickness is a feature that requires attention while designing for additive manufacturing. Bionic features are impossible to manufacture unless they are larger than the minimum printable feature size of the machine.

Material Choice

Different printing materials have different properties. Materials can be brittle or ductile, smooth or rough, flexible or solid, heavy or light, and so on. Choice of the right material for a specific application should meet the objectives of the machine. Engineering analogues constructed with homogenous materials show similar failure pattern propagation when compared to biological specimens. Experimental results by (Fratzl, 2007) show that biological lattice design strategies can be used to manipulate existing engineering materials. Hence, material science for additive manufacturing dealt in depth can be vital for bionic designs.

Printing curved surfaces/ File Resolution

An optimum number (fine) of polygons must be used to represent curved surfaces/ features. This will ensure a smooth finish of the manufactured part.

Build time

Build time depends on orientation, type of accuracy expected and the technique of printing.

Part strength

Additive manufacturing (mainly Fused Deposition Manufacturing) machines build parts that have inherently anisotropic properties that are stronger in the XY direction than the Z direction. In functional parts, it becomes important to consider the direction and the application of loads. For instance, FDM parts are much more likely to de-laminated and undergo fracture when placed in tension along its Z-direction as opposed to the XY directions.

Support Structures

Support material adds extra time, cost and material wastage to a manufactured part. Planned and optimal part orientation will reduce the consumption of support material and can also

4. Case Study - Bionic occurrence for a structural dome

The BREED procedure defined in the previous section has been leveraged to find possible bionic occurrences for a structural dome. Forms in nature which partially represent the dome include the mushrooms' head and wasp nests. Another interesting occurrence in nature is the *Oven* bird's nest. *Ovenbirds* are brown birds with rather short tails and fairly long bills. They are known for building mud nests that resemble old wood-fired ovens. These birds manage to work two thousand pellets of mud, weighing about ten pounds into a form which represents a dome. The oven's construction involves building a rather ordinary but oversized adobe cup on the branch. Figure 7 represents the engineering design space. The bionic form will be searched using the inspiration phase of BREED methodology.

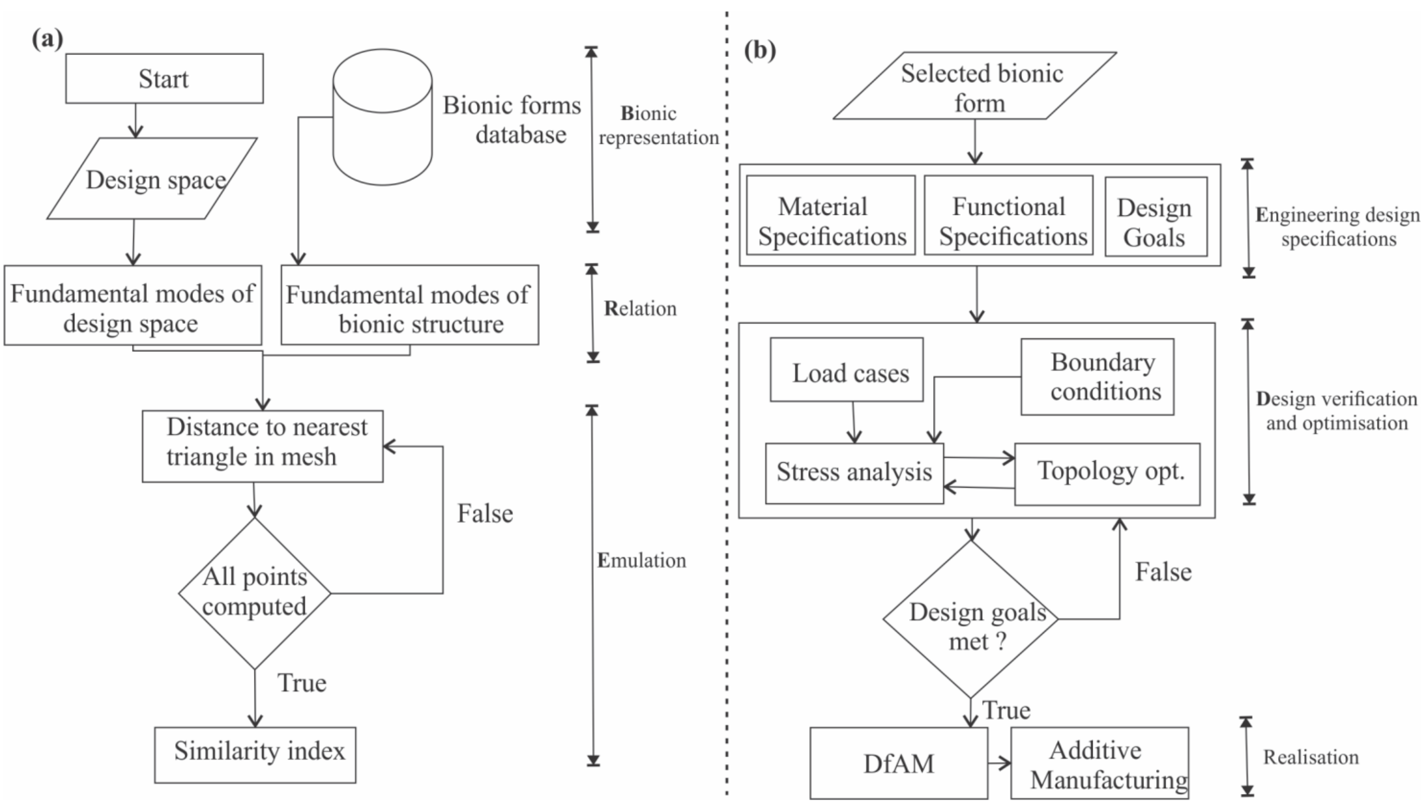

Figure 6 : A procedure based on BREED methodology (a) Obtaining bionic form inspiration for the design space (b) Procedure for the Validation phase of BREED methodology

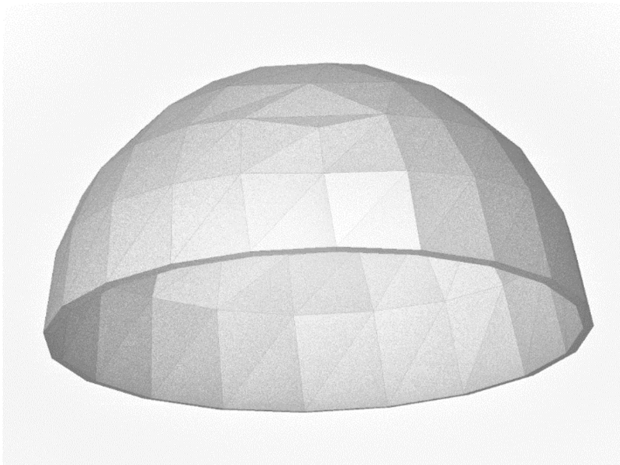

Figure 7 : Structural dome as the design space

The bionic database used in this case study consists of the discretised structures of nests, branches, crowns and beaks. The bionic models which are stored in the database after discretisation are retrieved for comparison. The dome is compared for form proximity using the other structures in the database. The first three non-zero Eigenmodes of the design space are compared with the respective Eigenmodes of the bionic form (Figure 8). Upon bringing the models for comparison to the same scale, the context of the forms is matched by the cloud to mesh algorithm. Further, the mode score is calculated from the histogram of distances (Figure 9).

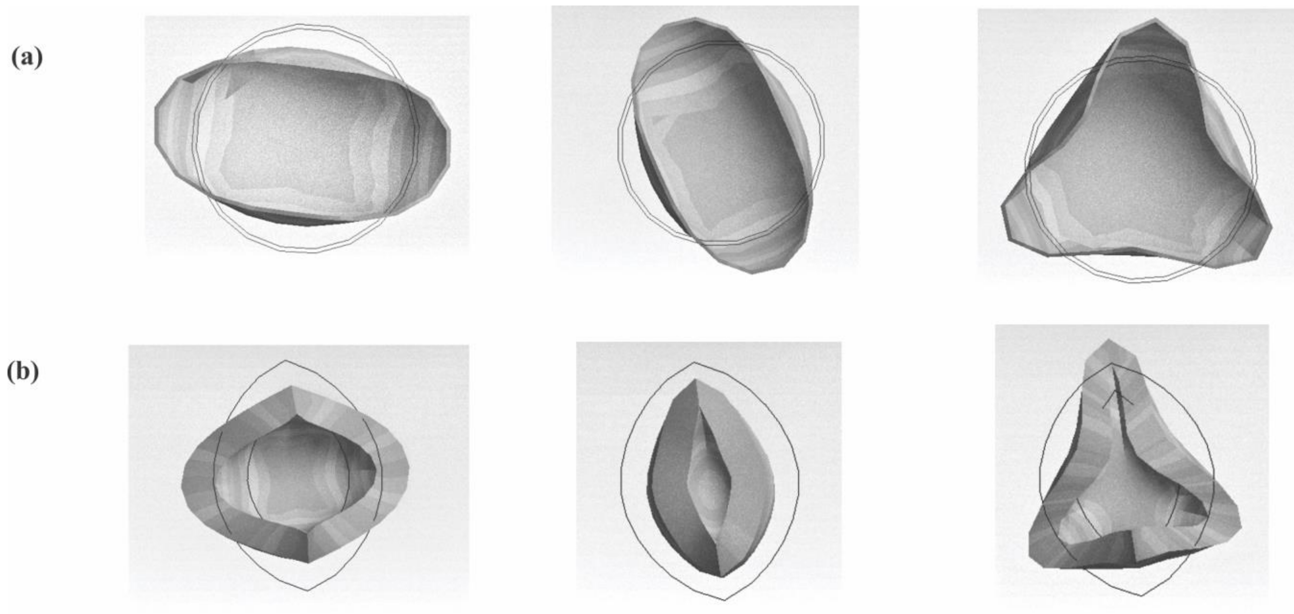

Figure 8 : Mode shapes of the two forms in consideration (a) Eigen modes of the structural dome (b) Eigen modes of the form of a mushroom

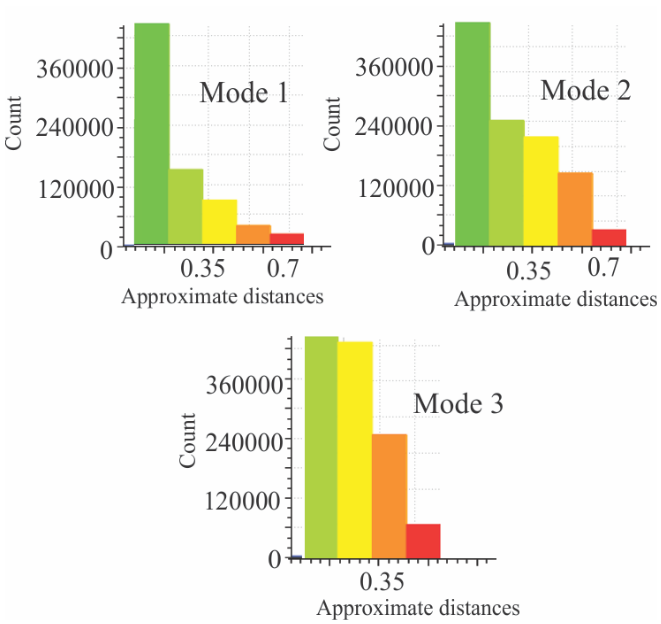

Figure 9 : Histograms of distances after comparison of eigen modes. The statistical mode shows the proximity to the design space

Based on the form similarity scores, bionic forms are suggested to the designer that can potentially be mimicked. A design problem does not have one solution. The designer can select from the array of suggested bionic forms. Here, the mushroom's crown has been selected by the designer. Upon selection of the bionic inspiration, geometric modifications are made to incorporate boundary supports, functional requisites and user requirements. Engineering specifications are developed to suit durability, strength and weight requirements. Structural analysis using finite element method is conducted to validate the structure. The design and exclusion regions for optimisation are determined by the load cases and boundary conditions. For this structure, the objective function is to reduce mass using constraints on Von Mises stresses and deformations. Topology optimisation is conducted using homogenisation and equivalent density methods. The optimised cross-section of the dome is shown in Figure 10(b).

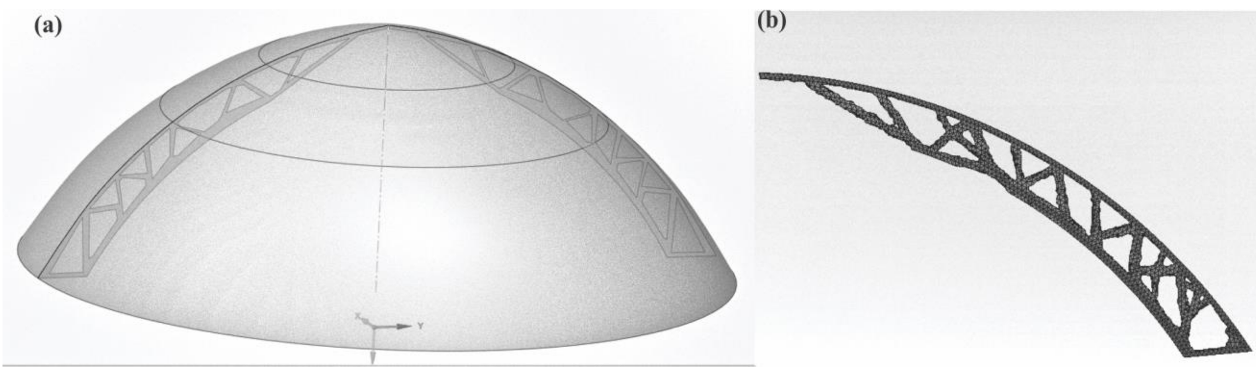

Figure 10 : Bionic structure after the inspire and validation phase of BREED methodology (a) The bionic dome inspired by the form of a mushroom (b) Cross section of the bionic dome after optimisation

Thus, using form matching and virtual prototyping, a bionic structure has been generated. Engineering specifications derived from functional and user requirements are imposed. The resulting structure is validated and optimised using proven numerical methods. The structure in Figure 10(a) is obtained using the BREED methodology. The 3D model shall be realised by additive manufacturing using the Fused Deposition Method.

5. 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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