DEVELOPING BIOMIMETIC DESIGN PRINCIPLES FOR THE HIGHLY OPTIMIZED AND ROBUST DESIGN OF PRODUCTS OR THEIR COMPONENTS

A Thesis

by

ANOSH PORUS WADIA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2011

Major Subject: Mechanical Engineering

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of Products or Their Components

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Approved by:

Chair of Committee,	Daniel A. McAdams
Committee Members,	Richard Malak
	Steven Smith
Head of Department,	Dennis L. O'Neal

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ABSTRACT

Developing Biomimetic Design Principles for the Highly Optimized and Robust Design of Products or Their Components. (August 2011)

Anosh Porus Wadia, B.S., Texas A&M University

Chair of Advisory Committee: Dr. Daniel A. McAdams

Engineering design methods focus on developing products that are innovative, robust, and multi-functional. In this context, the term robust refers to a product's ability to accomplish successfully its predetermined functions. Owing to the abundance of optimized and robust biological systems, engineering designers are now looking to nature for inspiration.

Researchers believe that biomimetic or bio-inspired engineering systems can leverage the principles, mechanisms, processes, strategies, and/or morphologies of nature's successful designs. Unfortunately, two important problems associated with biomimetic design are a designer's limited knowledge of biology and the difference in biological and engineering terminologies. This research developed a new design tool that addresses these problems and proposes to help engineering designers develop candidate bio-inspired products or solutions.

A methodology that helps users infer or extract biomimetic design principles from a given natural system or biomimetic product pair is described in this thesis. The method incorporates and integrates five existing design tools and theories to comprehensively investigate a given natural system or biomimetic product. Subsequently, this method is

used to extract biomimetic design principles from 23 biomimetic products and natural systems.

It is proposed that these principles have the potential to inspire ideas for candidate biomimetic products that are novel, innovative, and robust. The principle extraction methodology and the identified principles are validated using two separate case studies and a detailed analysis using the validation square framework.

In the first case study, two students and the author use the principle extraction methodology to extract characteristics from a natural system and a biomimetic product pair. Results from this case study showed that the methodology effectively and repeatedly identifies system characteristics that exemplify inherent biomimetic design principles. In the second case study, the developed biomimetic design principles are used to inspire a solution for an engineering design problem. The resulting solution and its evaluation show that the design's achieved usefulness is linked to applying the biomimetic design principles.

Similar to the TRIZ principles, the biomimetic design principles can inspire ideas for solutions to a given problem. The key difference is that designers using TRIZ leverage the solution strategies of engineering patents, while designers using the biomimetic design principles leverage nature's solution strategies. The biomimetic design principles are compared to TRIZ and the BioTRIZ matrix.

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1 INTRODUCTION

Consumer products continue to become more complex in order to meet an increasingly diverse set of customer needs. While meeting these needs is important, a product's market appeal and success also depends on it being robust, innovative, and reliable. In this research, robustness refers to a product's ability to successfully accomplish its predetermined functions within its designed-for environment [1].

To realize new products with such characteristics, researchers today are looking at nature's optimized, robust, and efficient systems for inspiration. There are, however, numerous problems associated with leveraging biology to develop bio-inspired engineering methods and/or products. Two important problems are an engineering designers' limited knowledge of biology and the difference in engineering and biological terminologies. This work presents a new design tool that could help bridge the gap between engineering and biology, thereby aiding the process of bio-inspired design.

Designers use numerous tools and methods to accomplish various tasks at different stages of the design process. These also include numerous methods that help with idea generation and conceptual design. Despite availability of such design methods, engineering products are often prone to failures. On the other hand, complex biological systems are found to be robust and very well adapted to their environment. Through years of evolution, nature has solved many important design problems and optimized those solutions for their respective environments.

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This thesis follows the style of the *Journal of Biomechanical Engineering*.

Biological systems can therefore inspire novel and innovative engineering products that are also robust and efficient. In fact, successful engineering products inspired by nature already exist and are referred to as biomimetic products. Many biomimetic products like Velcro® are a result of intuitive observations and unstructured design methods. The success of such products has encouraged designers to make deliberate attempts to find biology inspired engineering solutions. Biomimicry or biologically inspired design is the process of studying and leveraging the principles, mechanisms, processes, and morphologies from nature to solve engineering problems.

Researchers have proposed methodologies that help designers find potential solutions in nature and then translate them into the engineering domain [2-5]. Two important limitations on the successful implementation of such design tools are the design engineer's limited knowledge of biological systems and the difference in engineering and biological terminologies.

To this end, an engineering-to-biology thesaurus has been developed [6]. It provides a means to map terminology between two dissimilar domains by identifying synonyms. Taking the idea further, this research proposes developing a set of high-level abstract biomimetic design principles that could serve as a tool that helps designers develop innovative and robust biomimetic products or solutions.

To successfully develop such principles, we must first understand the differences in how nature does things versus how we do things. This research studies and analyzes 23 natural systems and biomimetic products to infer the underlying biomimetic design principles. The goal for this work is twofold:

1. Develop a methodology that helps identify design principles from a given biomimetic product pair or natural system. The natural system must exhibit sufficient potential for specific engineering applications.
2. Show that designers could use the biomimetic design principles to inspire ideas for candidate engineering solutions and products.

The first goal is satisfied by building on previous work that used the Theory of Highly Optimized Tolerance to study and analyze twenty biomimetic products [7]. This work develops a formal, coherent, and reproducible procedure that can be used to effectively ‘extract’ or infer design principles from key features, solution strategies, and functionalities of natural systems and biomimetic product pairs. The biomimetic principles are appropriately scoped and hierarchically grouped to ensure ease of use. The developed method is validated using the Validation Square technique [8].

The second goal refers to using the biomimetic principles as a design tool that inspires novel biomimetic solutions. Similar to the engineering design principles presented in the Theory of Inventive Problem Solving (TIPS/TRIZ), the biomimetic design principles can inspire novel biomimetic engineering products or solutions. This research uses two case studies to highlight the principle extraction methodology’s effectiveness and the resulting principles’ potential to inspire novel solutions.

Using the biomimetic design principles does not require a background in biology or even the knowledge of the natural systems from which the specific principles are inferred. The principles are based on nature’s optimized solution strategies, features, and functionalities. Therefore, the principles provide designers with inspiration for innovative products or solutions that are also bio-inspired and robust. In addition, the developed biomimetic design principles are also benchmarked against or compared to the existing TRIZ principles and the proposed BioTRIZ matrix [9, 10].

2 RELATED WORK

To develop biomimetic design principles that can help designers create innovative and robust bio-inspired products, this research draws on existing design tools and knowledge. Research in design has long been motivated by the need for products that are more efficient, robust, innovative, and appealing. As a result, researchers have developed many different product design methods and tools that help designers at different stages of the design process.

Shalizi reviews and discusses the various tools available to today's designer [11]. The review includes, but is not limited to assessing Design Structure Matrices, Agent Based Modeling, and Cellular Automata as design methods. In addition, other methods like the Theory of Inventive Problem Solving (TRIZ), Function Structure Analysis, and Analogy Based Design specifically aid designers in the concept generation phase. Function structure analysis or functional modeling helps represent the design problem or product in abstract terms and is often used with other idea generation tools during the conceptual design phase. Erden et al review functional modeling as a tool used in various design scenarios for different applications [12].

Within design research, this work focuses on the emerging area of biomimetic design. Through years of evolution, nature has solved many important design problems and optimized those solutions for their respective environments. Biology inspired design is the process of studying and leveraging the principles, mechanisms, processes, and morphologies of nature's successful design solutions to solve engineering problems.

Biomimetic designs methods include imitating natural process [13], copying biological structures [14], and drawing inspiration from a biological system [15]. As a relatively new field, the methodologies and applications of biology inspired design have not been fully developed and refined. These recent research efforts include using functional modeling, analogical reasoning, and the Theory of Inventive Problem Solving (TRIZ) to realize biomimetic designs [16].

Commonly used in the engineering design process, function modeling can help designers systematically, logically, and effectively model biological phenomena [17]. Tinsley et al show how the Functional Basis serves as an effective modeling language to transfer biological design solutions into the engineering domain [18, 19]. Analogical reasoning is commonly used in the engineering design process. In contrast, drawing analogies between biology and engineering is tougher and needs to be studied.

Glier et al describe three studies that examine the development and use of analogies in biomimetic design. The first to studies involved observing engineering students work on a design problem in a controlled laboratory environment with specific stimuli [20, 21]. In contrast, Vattam et al conducted an in vivo study of a design team in Georgia tech’s introductory course on biomimetic design [22]. The three studies highlight the usefulness of analogies in biomimetic design while also identifying weaknesses and areas that need to be studies further.

Often a designer’s limited background in biology makes it difficult to identify the appropriate biological systems or phenomena as the source of inspiration. To this end, a great deal of effort and research has focused on developing search tools that help identify the appropriate biological information. Researchers at the Biomimetics for Innovation and Design (BID) Laboratory, University of Toronto have developed a natural language search tool that uses engineering oriented keywords and their synonyms to search a biology textbook [23-25].

A common problem associated with searching for inspiration in biology is the difference in the languages of biology and engineering. It is therefore difficult to identify or find the appropriate biological phenomena using engineering keywords as search terms. To this end, Cheong et al used the BID Laboratory search tool to identify biologically relevant keywords for all the Functional Basis terms [26]. Nagel et al [6] developed an engineering-to-biology thesaurus by combining Cheong's keywords with similar sets produced at the Indian Institute of Science [27] and Oregon State University [28]. IDEA-INSPIRE [29] and Design by analogy to Nature Engine (DANE) [30] are two computer-based tools that allow users to interactively search and explore custom-built databases of biological and engineering systems.

Vincent et al have developed another tool called BioTRIZ, to help designers develop biomimetic solutions or products [5]. BioTRIZ is based on the Theory of Inventive Problem Solving (TRIZ) developed from studying nearly three million successful patents and vast stores of physical, chemical, and mathematical knowledge [31]. The TRIZ contradiction matrix is a look-up matrix that consists of 39 system parameters and 40 inventive principles. Each row and column is assigned to one of the 39 parameters, allowing the designer to choose which to maximize and minimize. The cells contain inventive principles that provide ideas to help solve the conflict highlighted in the design problem. After studying 500 biological phenomena with over 270 functions that form over 2500 contradictions, Vincent et al concluded that nature uses the same inventive principles, but uses them to solve different conflicts [10]. A reorganized TRIZ matrix, BioTRIZ reflects nature's solution strategies in a 6 by 6 matrix that retains the Altshuller's inventive principles but condenses the 39 system parameters into 6 operational fields. However, the method used to realize this transformation is not clearly highlighted in the published work [5, 32, 33].

The research presented here develops a methodology that extracts the underlying principles of nature's successful designs. This principle extraction methodology incorporates the use of functional modeling, the engineering-to-biology thesaurus, and morphological matrices. Existing natural systems or biomimetic product pairs can be analyzed using this methodology to identify their underlying principles, mechanisms, processes, and morphologies. Since they represent nature's solution strategies, the developed principles can serve as a design tool that helps designers create innovative bio-inspired engineering products. Using the abstract design principles does not require extensive knowledge of biology. It also eliminates the need to search a database of biological systems and phenomena.

Other important design tools this research draws on include the theory of highly optimized tolerance, the function-behavior-structure knowledge representation scheme, and the transformation principles development methodology. Proposed by Jean Carlson and John Doyle, the theory of highly optimized tolerance accounts for the tendency of interconnected complex systems to show robustness against uncertainties in a defined area, while displaying fragility elsewhere [1]. The tendency of a complex system or product to exhibit robustness in designed for environmental conditions is a desired design characteristic. Carlson and Doyle propose that this behavior is a result of the internal organization and structure of specific complex systems. Here, the theory helps establish the context for the analysis of natural systems and biomimetic product pairs.

Function-behavior-structure is a commonly used knowledge representation scheme in conceptual design. It captures the essence of the system and represents it in abstract terms. Designers can use the scheme for various design needs such as analogical reasoning, idea generation, and modeling complex systems [34, 35]. Here, the FBS representation scheme provides the framework for the questions asked of the system under analysis. The answers to these questions in turn highlight the natural system or biomimetic product's underlying biomimetic design principles.

The characteristics identified from investigating and examining natural systems and biomimetic product pairs are abstracted into 'heuristic' norms or high-level biomimetic design principles. These principles help translate the underlying robustness and efficiencies of natural and bio-inspired systems into the engineering domain. To provide a structure to this abstraction process, this research draws on a similar analysis previously performed by Sing et al to develop transformation principles [36]. These principles were identified through the analysis of numerous transforming products. They used a simple color-coded grouping and abstraction methodology that effectively translated the low-level characteristics identified into high-level design principles.

Design methodologies do not lend themselves to conventional mathematical validation methods. To help researchers validate design research and specifically newly proposed design methods, Seepersad et al present the validation square as a validation framework [37]. This framework helps evaluate the proposed design method in terms of its efficiency as well as its effectiveness through quantitative and qualitative measures respectively. The principle extraction methodology proposed here, is validated using the validation square framework.

3 RESEARCH APPROACH

Having identified the need for and the potential usefulness of creating a set of biomimetic design principles, the next logical step is to develop these principles. The approach proposed here is to use existing biomimetic product pairs and natural systems as a source of inspiration for the desired principles. With regards to this work, a biomimetic product pair refers to a given natural system and its corresponding bio-inspired engineering product. However, the proposed analysis includes only natural systems that inspire a potential engineering application or product.

We propose that analyzing natural systems and successful biomimetic product pairs can reveal the underlying characteristics and features that can be transferred from biology systems to bio-inspired engineering systems or products. In turn, a set of high-level principles of biomimetic design can be inferred through the abstraction of these observed characteristics, features, and low-level principles. Providing designers with a set of abstract principles also eliminates the need for in depth expertise in biology, zoology, or similar fields.

This proposed principle extraction methodology uses existing design tools and theories to effectively analyze a given natural system or biomimetic product pair. Following a comprehensive analysis, the underlying characteristics and features can be identified. These are then abstracted into useful high-level biomimetic design principles. The following subsections present a detailed discussion of the design tools and the developed principle extraction methodology.

3.1 Design Tools

This research presents a new and unique methodology that results in the extraction of biomimetic design principles from the analysis of natural systems and biomimetic product pairs. These biomimetic design principles can serve as a tool that helps designers create innovative and robust candidate bio-inspired solutions or products.

This research builds on previous work by incorporating and integrating various existing design tools and theories into a single coherent methodology. The resulting methodology helps comprehensively analyze biomimetic product or natural systems to identify their underlying biomimetic design principles.

The principle extraction methodology incorporates five design tools or theories: function modeling, morphological matrices, the theory of highly optimized tolerance, the function-behavior-structure representation, and a color-coding abstraction methodology. In addition to these tools used in the principle extraction methodology, this research also uses the validation square method to evaluate the developed methodology. This subsection presents an overview of the background and implementation procedures for each of the five aforementioned tools.

3.1.1 Functional Modeling

Commonly used in the conceptual design process to aid with idea generation, functional modeling is a well-defined process that enables the representation and understanding of the customer needs for a given design problem or product. Erden et al highlight the usefulness of functional modeling while reviewing its various approaches and applications [12].

At its basis is the notion of a function structure put forwards by Pahl and Beitz [38]. A function structure is a meaningful breakdown of the system's overall function into sub-functions connected through material, energy, and/or signal flow combinations. As defined by Otto and Wood, a function of a product represents the relationship between an input and a desired output of a product irrespective of its particular form [39]. The product's overall function is what it is intended to do and is stated in a verb-noun (or verb-object) format [38].

The functional modeling process starts with building a black-box model. This model captures the overall function of the system without focusing on its constituent sub-functions. It also states the system's overall inputs and outputs in terms of material, energy, and/or signal flows. For example, consider the black box model for a bicycle presented in Figure 1 below.

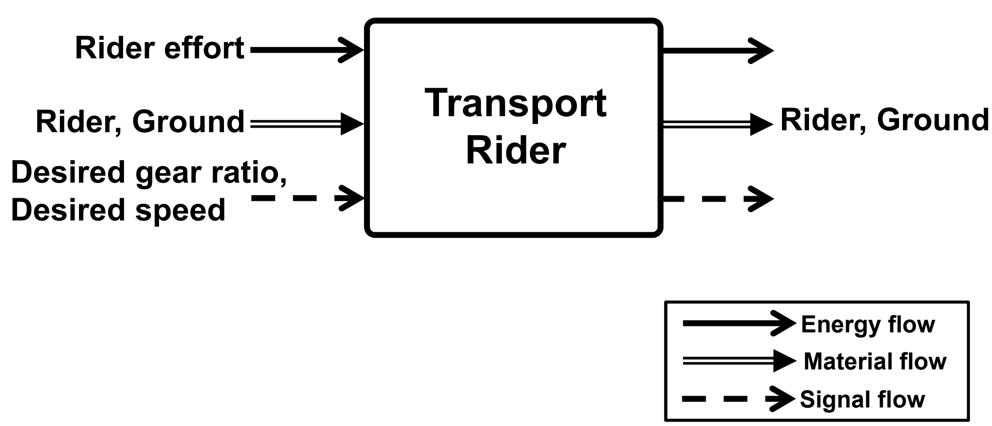


Figure 1: Black box model of a bicycle [2]

Once black-box model is established, the functional model for the system can be developed. This includes breaking the system's overall function down into a 'network' of sub-functions connected by material, energy, and/or signal flows. It is important to note that like the overall function, each sub-function is stated in a verb-noun (or verb-object) format. To help with the effective and accurate representation of sub-functions within the extensive product space, Hirtz et al developed a unified functional language called the Functional Basis [19]. It provides a generic set of function and flow terms that allow for a uniform function-flow representation while modeling varied products. Functions and flows are classified from the general to the specific and presented in three levels: primary, secondary, and tertiary.

Graphically, the functional model consists of a set of rectangular blocks that represent sub-functions and three sets of arrows that represent the three types of flows. A Functional Basis term in each block defines how the input flows to that block are acted upon resulting in specific output flows [40]. The bicycle's functional model is presented in Figure 2 as an illustrative example.

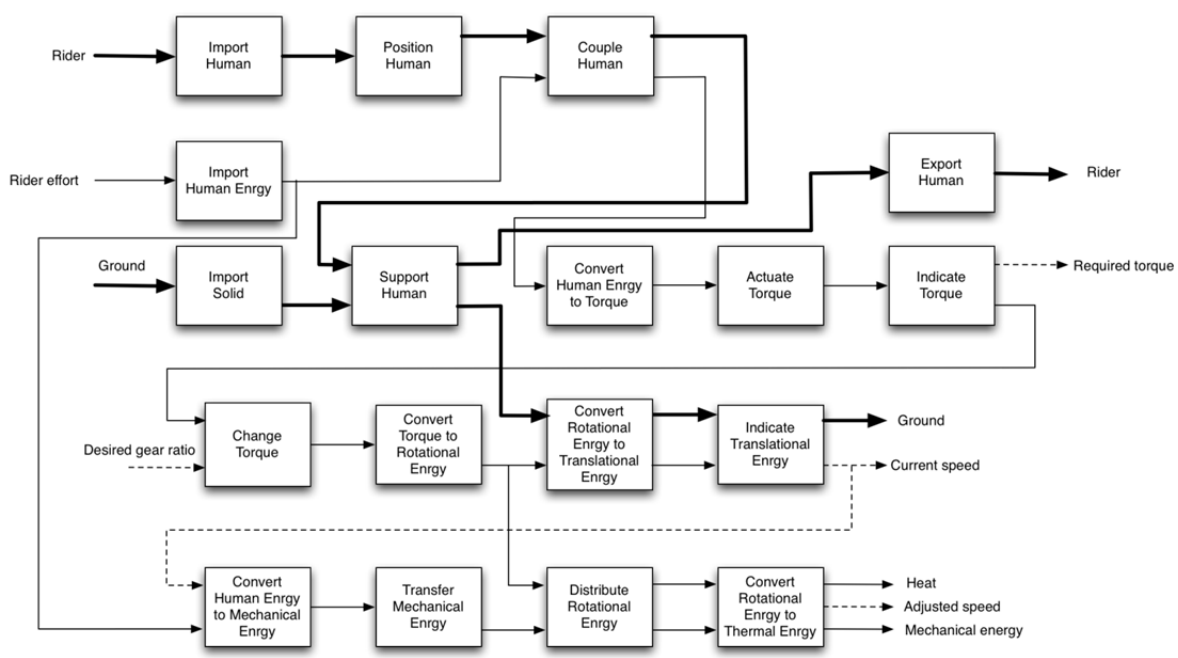


Figure 2: Functional model of a bicycle [2]

Functionally modeling a product in this way leads to an abstract representation of the design needs that is independent of the physical system components under consideration. In other words, it allows the designer to breakdown the overall function (or black-box function) into sub-functions without fixating on a particular physical solution.

Nagel et al and Tinsley et al have proposed the use of functional modeling in biomimetic conceptual design [18, 41]. They presented preliminary efforts at functionally modeling natural systems and using the representations to develop biologically inspired engineering solutions. As pointed out by Nagel et al, such an approach leverages the advantages of functional representation. The advantages of functionally representing biological systems include the following:

1. It systematically establishes and represents functionality without regard to the physical components that implement that functionality.
2. It captures the modeled system's functionality, morphology, and/or strategy at multiple levels of fidelity.
3. It allows for the identification of a biological system's characteristics or features that can be imitated by engineering means.
4. It promotes creativity in concept generation.
5. It allows for representing the system's information in an easy function-flow format.

With these advantages in mind, Nagel et al develop a general methodology that helps engineering designers functionally model natural systems. Consequently, the functional models of the natural systems are used in a concept generation methodology.

On the other hand, this research proposes adapting the functional modeling methodology (from Nagel et al) for use in meeting a different set of needs. Instead of using biological systems' functional models to develop engineered solution; the new approach aims at using functional modeling as a tool to analyze existing biomimetic product pairs or natural systems. The goal of the proposed analysis is to identify the underlying characteristics, features, and principles transferred from the natural system to the bio-inspired engineering system. These would then be abstracted into high-level biomimetic design principles that can be used to develop biologically inspired products.

However, functionally modeling a natural system is not a simple task due to the inherent difficulties in establishing the scope and scale of the system [41]. To achieve comparable well-defined functional models for natural systems, Nagel et al propose the use of biological categories and scales during modeling.

Biological categories

When modeling a biological system, indentifying the category it best fits into can help guide the functional model creation. Based on conclusions from previous research efforts, the four categories are defined as follows [41].

Physiology: Functions and activities of a biological system

Morphology: Form and structure of a biological system

Behavior: Responses of a biological system to internal and external stimuli

Strategy: Common behavior exhibited by multiple biological systems to fulfill different needs.

Biological scale

Establishing the biological scale of the system also helps define the functional model's boundaries. In fact, Tinsley et al argue that functionally modeling a biological system at multiple scales can result in multiple inspirations for engineering products [3]. Therefore, in (Nagel et al) the designer is advised to consider modeling the natural system at varying scales to increase the probability of inspiring multiple engineering solutions.

However, for this research the criteria stated earlier requires that a natural system must be considered for this method only if it has the potential for a specific engineering application. Therefore, the key here is to functionally model the biological system at the scale at which it inspired the envisioned engineering product.

The detailed methodology adapted from Nagel et al and used here to model natural systems is presented in the subsection titled: Developed Principle Extraction Methodology.

3.1.2 Morph Matrices

The morphological matrix is a tool that helps designers search, compare, and combine concepts during product design [39]. In its most commonly used form, a morphological matrix's first column lists each of the product's functions from its functional model. Each function then represents a row in the matrix. The second column generally lists the current solution for each of the listed functions, if it exists. The rest of the columns are used to record all the new solutions developed for each function. These new solutions are developed using various idea generation techniques. Figure 3 shows the described morphological matrix.

Functions	**Solution methods**				
	1	2	⋯	⋯	m
F_1	S_{11}	S_{12}	⋯	⋯	S_{1m}
F_2	S_{21}	S_{22}	⋯	⋯	S_{2m}
⋮	⋮	⋮	⋯	⋯	⋮
⋮	⋮	⋮	⋯	⋯	⋮
F_n	S_{n1}	S_{n2}	⋯	⋯	S_{nm}

Figure 3: Basic format for a morphological matrix

Once filled in, the matrix allows a designer to compare and combine ideas to develop diverse concept variants for the overall product. Pahl and Beitz highlight the advantages as well as issues related to using the morphological matrix as a tool that helps combine solution strategies [38]. A key part of combining various solutions is to ensure the smooth flow of energy, materials, and/or signals.

However, this research uses a modified morphological matrix format. This new format allows a designer to compare natural systems or bio-inspired products and a conventional product. Tinsley et al perform a similar analysis that involves using morphological matrices to compare the natural system solution to those of an engineering system [3]. Their approach is adapted here to compare the natural system's function-flow pairs and their solutions to those of a conventional engineering product. This comparison forms a part of the biomimetic design principle extraction methodology presented in this research.

3.1.3 Theory of Highly Optimized Tolerance (HOT Theory)

Research in engineering design continues to explore new avenues while also improving our understanding of existing concepts [11]. As a result, today's designers have access to numerous design tools that help with the product design process. These include tools that help establish customer needs, generate conceptual ideas, and also guide the detail design process. However, despite these advances and the availability of such design tools many engineering systems and products often experience failures. Failures are an undesirable feature for any product and reducing their occurrence through better product design is very important. Designers purposefully design systems to be robust to common predicted uncertainties.

As a result, researchers have studied failures within engineering systems in an attempt to better understand their trends and behaviors. Failure tendencies of many natural and engineered complex systems have been shown to follow a power law behavior [42]. The theory of self-organized criticality attempts to explain this phenomenon within various complex systems [43]. Similarly, Jean Carlson and John Doyle proposed the theory of highly optimized tolerance to account for the tendency of interconnected and complex systems to show robustness against uncertainties in a defined area, while displaying fragility elsewhere [1].

Interestingly, natural systems exhibit robustness, in that they accomplish their overall functional objectives in the face of designed-for environmental uncertainties [1].

For example, organisms and ecosystems are remarkably robust to variations in temperature, nutrient supplies, moisture, and predators; but these systems are catastrophically sensitive to small perturbations like genetic mutations, an exotic species, or new viruses. Consequently, the theory of highly optimized tolerance provides the means and context for the analysis of natural systems and biomimetic product pairs resulting in the identification of the proposed biomimetic design principles.

The biomimetic design principles proposed here, aim to leverage those solution strategies that make natural systems robust to their designed-for environments. The designed-for environment refers to anticipated uncertainties and excludes chance or 'freak' external disturbances. Carlson and Doyle suggest that the internal organization and structure of specific complex systems make them highly tolerant and robust to their designed-for environment. Again, the term robust as used here relates to a product or design's ability to successfully accomplish its predetermined functions.

They use a simple forest fire model as a supporting example. A highly optimized tolerant state for the forest refers to an optimal distribution of trees with regularly distributed firebreaks to ensure a high timber yield and low fire spread. This HOT system is robust to anticipated dangers like forest fires, but highly susceptible to design flaws since a forester cannot consider all possible scenarios. Contrastingly, a random distribution of trees could result in uncontrolled responses to a spark. Beyond a certain 'critical' density, the spark could cause complete devastation. Therefore, the key consideration in a HOT system is its design; which allows it to sustain conditions that could cause instability for an arbitrarily designed system [44].

In short, the HOT theory suggests that highly interconnected, non-self similar complex systems can be robust in the face of anticipated and designed-for conditions; and yet be too fragile to sustain unexpected events. As explained earlier, lower failure rates in the face of designed-for environmental conditions are a desired, if not end all goal of complex system design. Thus, complex systems that display a highly optimized tolerant state can be considered desirable.

With regards to this research, the HOT theory helps establish the context for the analysis of natural systems and biomimetic product pairs. This analysis results in identifying underlying biomimetic design principles that inspire innovative bio-inspired engineering products or solutions. Reviewing a product or system in the context of this theory helps the researcher ask and answer specific questions of the product or system. These answers help identify underlying bio-inspired sub-functions, features, structures, strategies, and behaviors that are in turn abstracted into biomimetic design principles.

3.1.4 Function-Behavior-Structure (FBS) Representation

Function, behavior, and structure form a knowledge representation scheme that can bridge the gap between human intention and physical behavior of systems at the conceptual design stage. The FBS framework is widely recognized as a tool that helps effectively articulate the description of a system. Functional representation serves as an important means to capture the design activities and choices within the design process [45].

As a knowledge representation scheme, the FBS framework has varied applications in conceptual design that include system modeling, idea generation, as well as developing and maintaining system design repositories [35, 46]. Additionally, it can also serve as a tool that enables analogy-based design. Qian et al show that how the FBS scheme can be used to represents systems in varied design domains [34].

In this research, FBS representation helps frame the questions used to examine a natural system or biomimetic product pair under review. Since the FBS representation scheme effectively captures the essence of a system; we can conversely state that it could also help effectively explore a system. Therefore, questions are formulated in a way that explores the function, behavior, and structure of the system under analysis.

Together, the context provided by the HOT theory and the questions based on the FBS framework can help identify the underlying bio-inspired sub-functions, structures, strategies, and behaviors of bio-inspired products and/or natural systems.

3.1.5 Developing Transformation Principles: Color-coded Principle Abstraction

The abstraction process referred to in subsection 3.1.3 involves reviewing the identified characteristics in an effort to establish ‘heuristic’ norms or high-level biomimetic design principles. These principles help designers leverage the underlying robustness and efficiencies of natural and bio-inspired systems. There are two key issues that must be addressed to ensure the effectiveness of this proposed abstraction process. Firstly, the proposed abstraction is inherently subjective and results could vary from user to user. Secondly, there is a need to abstract the characteristics (identified from the analysis of natural systems and biomimetic product pairs) into high-level principles that are at the same hierarchy, scope, and scale.

To address these issues, this research uses a structured, coherent, and repeatable method that effectively accomplishes the desired abstraction. In addition, the research also defines guidelines for a biomimetic design principle to ensure the effective abstraction of the identified characteristics.

The requisite structured abstraction method is adapted from a similar process used by Singh et al to developed transformation principles through the analysis of numerous transforming products [36]. They use a simple color-coding system that simplifies and structures the abstraction process.

There are numerous advantages to using such a color-coding system. Color-coding helps the user to easily group and track the identified characteristics based on common features, functional elements, structures, strategies, and/or behaviors. Often a single characteristic could contribute to different groups and with color tags one can manage such overlaps. The color-coding scheme's most important advantage is that it makes the process of reviewing a large number of characteristics identified from natural systems and biomimetic product pairs manageable.

This scheme also lends itself to tracking at various levels of abstraction as the characteristics are grouped and converted into high-level biomimetic design principles. The simplicity of this method makes it robust and effective ensuring that none of the characteristics are missed or overlooked during the review.

3.1.6 Validation Square Method

This research proposes the development of a tool that helps designers leverage nature's efficient and optimized solutions to create innovative bio-inspired engineering products. The goal is broken down into two parts:

1. Develop a methodology that helps identify design principles from a given biomimetic product pair or natural system. The natural system must exhibit sufficient potential for specific engineering applications.
2. Show that these principles can help designers develop innovative biomimetic engineering solutions.

The proposed principle extraction methodology builds on previous work within biomimetic design and also incorporates existing design tools. As with most newly proposed design methods or tools, it is difficult to validate the methodology beyond all doubt. In fact, design methods do not easily lend themselves to a rigorous numerical analysis and validation procedure. To this end, Seepersad et al have developed a technique that helps researchers validate such design methods [37]. It is based on the assertion that validating a design method is a process of demonstrating its usefulness with respect to some predetermined purpose. For the design method presented in this work, the predetermined purpose is twofold. The first goal is to effectively develop biomimetic design principles. The second is to show that these principles can help designers create innovative biomimetic engineering solutions.

The validation is divided into two parts: structural validation and performance validation. Figure 4 shows the validation square, which outlines the different validation aspects the design method must meet.

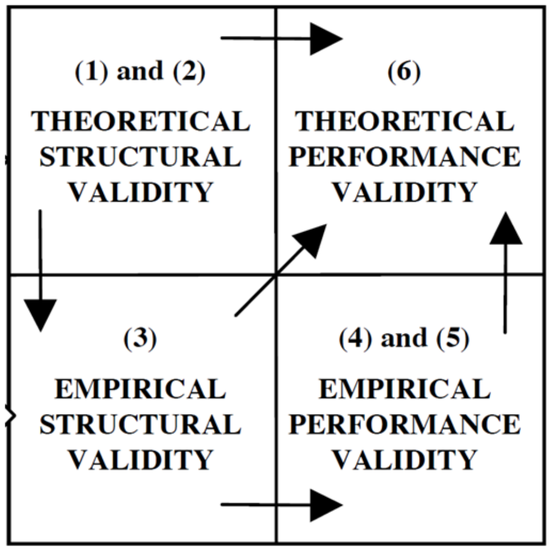


Figure 4: The validation square framework [37]

Therefore, a design method is considered valid if it is shown to meet the 6 validity criteria. Evaluating the design method using this process helps assess its effectiveness and efficiency based on qualitative (1, 2, and 3 in Figure 4) and quantitative (4, 5, and 6 in Figure 4) measures respectively. In this case, efficiency refers to the biomimetic design principles' ability to inspire innovative and robust candidate solutions or products. The following subsection discusses each structural validation criteria and each performance validation criteria in detail.

Structural validation: Qualitative process

The structural validation of a proposed design method proves its effectiveness with regards to the predetermined goals. To be considered structurally valid, the following aspects of the design method must be acceptable.

1. Accepting the individual constructs constituting the method: The design method proposed in this research incorporates the five design tools: functional modeling, morphological matrices, the theory of highly optimized tolerance, the function-behavior-structure framework, and a color-coding abstraction methodology. Each of these methods or techniques is critically analyzed and reviewed. Evidence for their successful implementation and application potential helps underline their usefulness.

2. Accepting internal consistence of the way in which the constructs are put together in the method: The key here is to review the way in which the various design tools are put together to make up the proposed principle extraction methodology. A detailed analysis of the method helps establish its logical internal consistency.

3. Accepting the appropriateness of the example problems that will be used to verify the performance of the method: The first case study evaluates the effectiveness and repeatability of the principle extraction methodology. The second case study evaluates the usefulness of the biomimetic design principles themselves. The method and objectives for each case study are reviewed to ensure they are

appropriate exercises. It is important that the selected case studies effectively evaluate all the aspects of this research.

Performance validation: Quantitative process

Validating the proposed method's performance proves its efficiency in achieving the predetermined goals. The performance validity required that the following aspects of the design method be acceptable.

4. Accepting that the outcome of the method is useful with respect to the initial purpose for some chosen example problem: In the first case study, the principles extraction methodology is used multiple times by different users to evaluate its effectiveness and repeatability. Examining the different principles identified will help assess the effectiveness and repeatability of the proposed methodology. For the second case study, the developed bio-inspired solution must meet all of the design requirements effectively. This is shown using CAD models, stress-strain analysis, and prototype testing. In addition it is compared to other concepts developed using different idea generation methods.

5. Accepting that the achieved usefulness is linked to applying the method: For each case study the results must not only satisfy the predetermined goals, but they must be a consequence of using the proposed methodology or design principles. Therefore, each case study's results are traced back and connected to the use of

the methodology or principles. This helps assess the usefulness of this research with regards to the predetermined goals.

6. Accepting that the usefulness of the method is beyond the case studies: The scope of this study does not include the actual implementation of the designed concept.

3.2 Developed Principle Extraction Methodology

To comprehensively infer the underlying biomimetic design principles, the proposed principle extraction methodology must be formal, effective, and repeatable. A formal method is one that logically guides a user to effectively achieve the goal. In other words, the process is sequentially organized and not vague or unstructured. The method's effectiveness refers to its ability to infer biomimetic design principles from a given set of biomimetic product pairs or natural systems.

In this case, the effectiveness is inherently tied to that of the method's constituent theories and tools: the theory of highly optimized tolerance, functional models, morph matrices, and the transformation principles' abstraction method. The proposed methodology will incorporate and integrate these existing tools, theories, and methods in a structured manner. Figure 5 below presents a flowchart overview of the proposed principle extraction methodology.

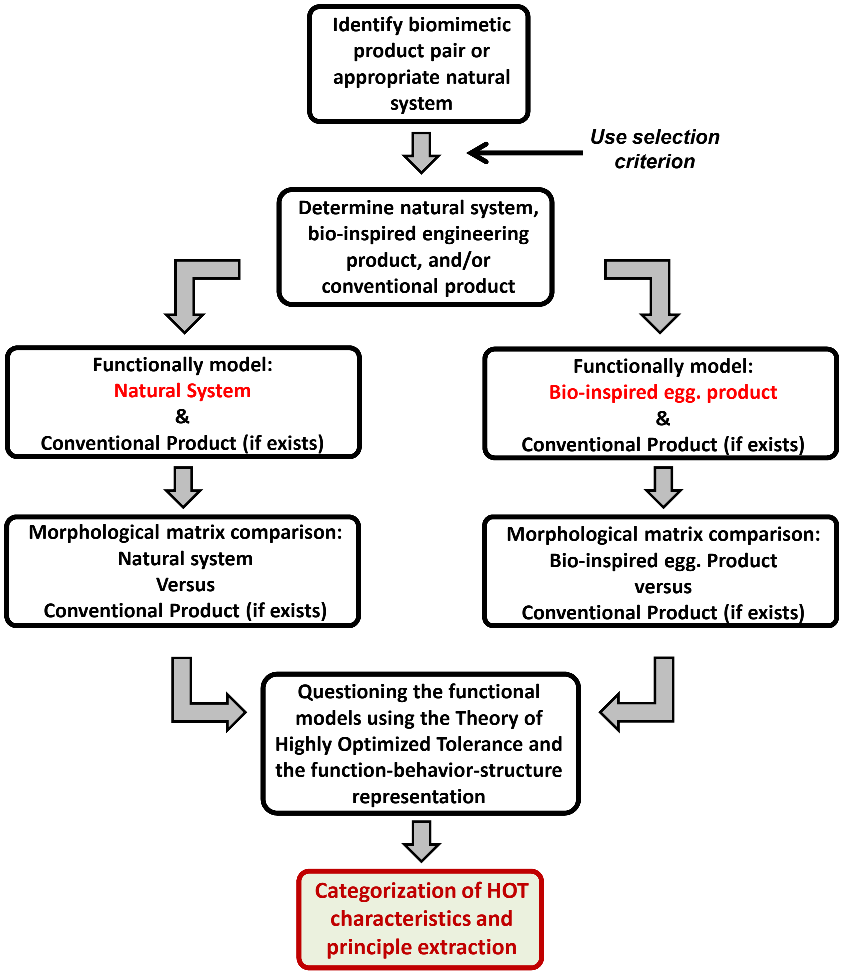


Figure 5: Proposed principle extraction methodology

Each step of the sequentially organized principle extraction methodology and the specific design tools used therein are explained in detail below.

3.2.1 Step 1: Identify Biomimetic Product Pair or Appropriate Natural System

The subsequent methodology's success depends on the selection of a biomimetic product pair or natural system to be analyzed. Not all biomimetic product pairs or natural systems lend themselves to an effective analysis using the principle extraction methodology presented here. It is therefore important to define a set of criteria against which each biomimetic product pair or natural system is tested before the rigorous analysis is performed.

The overall criterion is divided into two parts: preliminary criteria and secondary criteria. Therefore, only those products or systems that meet the first part are considered for the thorough examination in the second part. The primary criteria and secondary criteria are outlines below.

Preliminary requirements/criteria

Any biomimetic product pair or natural system analyzed using the developed methodology must meet the following two criterions.

1. *Innovative biomimetic product pair or natural system*

   A biomimetic design concept or product is considered for further analysis if it is considered to be novel, new, and creative. A natural system is considered for further analysis if it displays sufficient potential for a specific engineering application that is novel, new, and creative.

2. *Sufficient knowledge of the biomimetic product pair (both the natural system and the bio-inspired engineering system) or natural system (both the natural system and the proposed bio-inspired engineering system) must be available to allow for a comprehensive analysis of its working*

   Without a detailed understanding of the product or system's components and working, it is very difficult to identify characteristics that make it robust in terms of achieving its functions. This criterion is aimed at avoiding the analysis of newly proposed biomimetic products with insufficient information regarding its components, performance, and working.

Secondary requirements/criteria: Elimination

Concepts, products, or systems that fall under the following categories are not considered in this research and cannot be analyzed using the developed methodology. This is primarily because such systems/products do not lend themselves to a straightforward analysis using the theory of highly optimized tolerance, which forms a part of the subsequent methodology. Additionally, this helps scope the problem to allow for a comprehensive analysis of a limited number of systems. All the categories of proposed biomimetic products not considered in this research are listed below.

1. *Imitating the motion of a natural system*

   Imitating motions of specific natural systems (like insect's locomotion, fish's body motion, and insect's wing motion) can be beneficial for certain engineering applications.

   Unfortunately there exists a large disparity in the material properties and abilities of a biological system in comparison to a mimicking engineered system.

   As a result, it is difficult to use the developed methodology to analyze and compare the motion of specific natural systems or biomimetic systems to conventional systems.

2. *Imitating the behavior of a biological community*

   Insect foraging and other social activities have provided inspiration in the areas of adaptive controls and robotics.

   It is difficult to analyze specific behaviors in terms of their robustness. Other considerations that are hard to quantify and relate to engineering features are the possibility of learning over time and intelligence. Additionally, inspiration in terms of individual interactions within communities is very abstract and identifying such a system's robust characteristics is not effective or reliable.

3. *Copying chemical compositions from nature*

   It is difficult to characterize a given chemical compound or composition as robust. Secondly, a chemical composition or compound cannot be classified as a complex system (at a macro level) and therefore doesn't lend itself to an analysis using the theory of highly optimized tolerance.

   It is important to note that engineering systems inspired by natural composites can be analyzed using the developed methodology and must not be eliminated. This includes constituent compounds or material put together at a macro level (as opposed to the molecular level) with specific attention paid to the structural arrangement. Examples of such biological systems include the red abalone snail's shell and the toucan's beak.

4. *Processes or methods used to manufacture a biomimetic product*

   Unlike the biomimetic product itself, processes or methods used to manufacture biomimetic products do not incorporate characteristics inspired by natural systems. As a result, analyzing them is not fruitful with respect to the eventual goal of creating a set of biomimetic design principles.

Before analyzing a specific biomimetic product pair or natural system using the developed methodology, it must be tested against all the above criteria. If it falls under any of aforementioned categories, the developed methodology would not be successful in identifying the underlying biomimetic design principles (if there are any present).

3.2.2 Step 2: Determine Natural System, Bio-inspired Engineering Product, and/or Conventional Product

This step is performed once the biomimetic product pair or natural system (to be analyzed) has met all the required criteria. The process for each case (analyzing a biomimetic product pair and a natural system) is separately outlined below.

1. *Biomimetic product pair*

In the case of a biomimetic product pair, the biological/natural system that inspired it is identified. Second, the corresponding conventional engineering product is identified if it exists. The term conventional product used here refers to an existing product that is not bio-inspired, but accomplishes the same overall function. An example of a biomimetic product pair is shown in Figure 6 below.

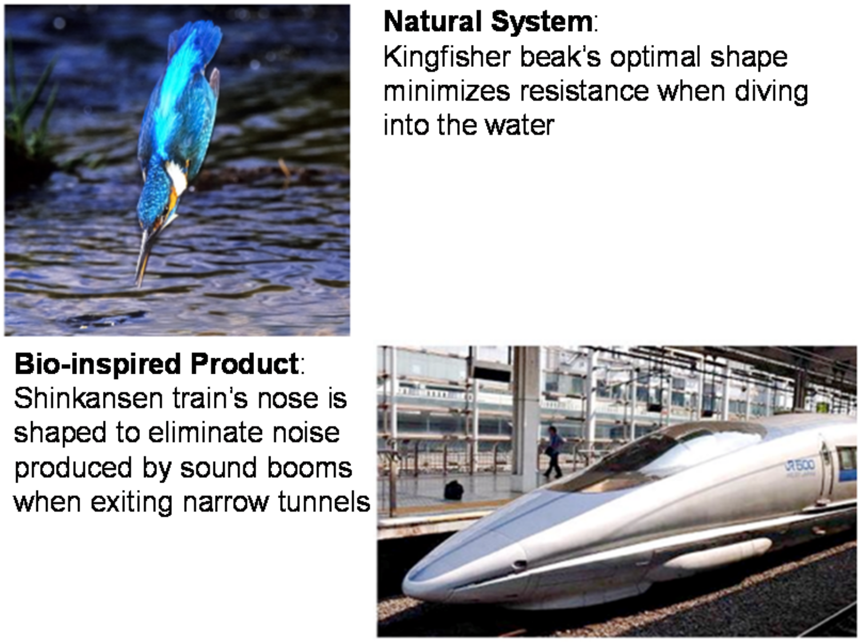


Figure 6: The shape of the Shinkansen train's nose is inspired by the Kingfisher's beak

2. Natural system

In the case of a natural system, its prospective or proposed bio-inspired engineering product and its proposed application or overall function are identified. Next, the corresponding conventional engineering product is identified if it exists. Again, the term conventional product used here refers to an existing product that is not bio-inspired, but accomplishes the same overall function. An example of a natural system and the corresponding prospective bio-inspired product is shown in Figure 7 below.

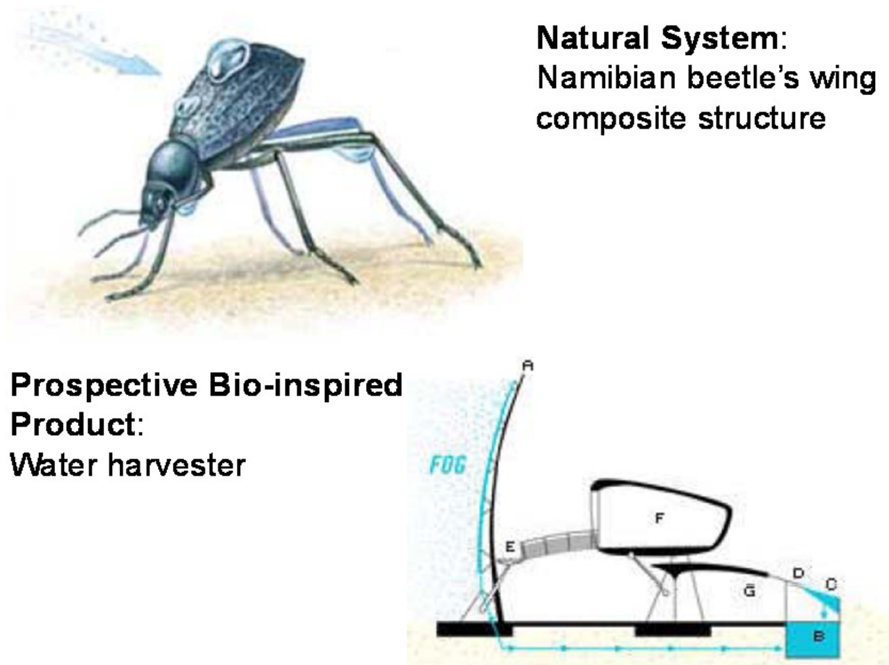


Figure 7: The Namibian beetle's composite wing structure inspires prospective water harvester that can collect water from fog

3.2.3 Step 3: Functional Modeling

Once the natural system, bio-inspired engineering product, and/or conventional product are identified, they are functionally modeled.

Nagel et al have leveraged the functional modeling methodology to model natural systems and use those models to help in concept generation [41]. However, this research proposes using the functional modeling methodology to meet a different set of needs: identifying characteristics, features, and principles transferred from the natural to the engineering domain through the analysis of functional models for natural systems and biomimetic product pairs.

With this distinctive goal, the functional modeling methodology (from Nagel et al) is adapted or modified to model natural systems and bio-inspired engineering products. The methods used to functionally model natural systems and bio-inspired systems are presented in detail below.

1. Natural system functional modeling method

The method guides a user to develop a correct, accurate, and effective functional model for a natural system.

1. Review and understand the natural system specifically in terms of its proposed bio-inspired engineering application/product
    - Understand the detailed working of the natural system specifically the aspects that inspire the proposed bio-inspired engineering product or application.

2. Define the design question solved by the proposed bio-inspired engineering product
    - Pose a design question whose solution is the proposed bio-inspired engineering system.
    - It must highlight the overall function of the product and any constraints associated with the product's design.

3. Define the category and scope of the functional model
    - Review the four biological categories:
        - Physiology: Functions and activities of a biological system
        - Morphology: Form and structure of a biological system

    - Behavior: Responses of a biological system to internal and external stimuli
    - Strategy: Common behavior exhibited by multiple biological systems to fulfill different needs.
  - Use the inspired engineering product's viewpoint to determine the category that best captures the inspiring features of the natural system.
  - This information helps scope the functional model and defines its boundaries.

4. Define the desired scale of the model
  - Compare the natural system and the proposed bio-inspired engineering system to identify the appropriate scale for the functional model.
  - The chosen scale must capture the natural system's sub-functions, features, structures, strategies, or behaviors that inspire the proposed engineering product or application.

5. Functionally model the natural system within the bounds set by the design question, biological category, and biological scale.
  - Use the engineering-to-biology thesaurus to suitably represent biological flows and functions in the functional basis terminology.
  - Use basic functional modeling guidelines to accurately model the system [40].

6. Check and/or validate the functional model against the design question and black box model

- Ensure that all the function-flow pairs are represented using the functional basis terms. Use the engineering-to-biology thesaurus as a guide.
- Ensure that the functional model captures the natural system's sub-functions, features, structures, strategies, or behaviors that inspire the proposed engineering product or application.

2. Bio-inspired system functional modeling method

Modeling bio-inspired engineering products and conventional products does not require all the steps mentioned above. The modified approach for modeling bio-inspired engineered products and conventional products is presented below.

1. Review and understand the bio-inspired engineering product or conventional product.
    - Understand the detailed working of the product.
    - For the biomimetic product it is important to understand the sub-functions, features, structures, strategies, or behaviors of the product inspired by nature.

2. Define the design question solved by the proposed bio-inspired engineering product or conventional product
    - Pose a design question whose solution is the proposed bio-inspired engineering system.
    - It must highlight the overall function of the product and any constraints associated with the product's design.

3. Define the desired scale of the model
    - The functional model should be scaled to include the sub-functions, features, structures, strategies, or behaviors inspired by nature.

4. Functionally model the system within the bounds set by the design question, biological category, and biological scale
    - Use basic functional modeling guidelines to accurately model the system [40].

5. Check and/or validate the functional model against the design question and black box model
    - Ensure that all the function-flow pairs are represented using the functional basis terms.
    - Ensure that the bio-inspired engineering product's functional model captures the sub-functions, features, structures, strategies, or behaviors inspired by nature.
    - The conventional product's functional model should be similarly scoped (in terms of functionality) to that of the natural system or bio-inspired engineering product.

Working through the functional modeling steps detailed above, results in the development of the specific functional models for a biomimetic product pair and/or a natural system as seen in Table 1 below.

Table 1: Specific functional models are developed when analyzing a natural system and/or a biomimetic product pair

Original system/product pair chosen for analysis	**Functional models developed**
Biomimetic product pair	Bio-inspired engineering system model Conventional engineering product model (if exists)
Natural system	Natural system Conventional engineering product model (if exists)

In step 4 and step 5, the developed functional models are compared and reviewed to infer the underlying characteristics, features, and principles transferred from the biological domain to the engineering domain.

3.2.4 Step 4: Comparison Using Morphological Matrices

The functional models are now compared using the morphological matrix method. Each functional model is then comprehensively reviewed within the context of the theory of highly optimized tolerance in step 5.

A morphological matrix based comparison is performed only when the corresponding conventional product exists, otherwise step 4 is skipped. In this context, a conventional product is defined as an existing marketed product that is not bio-inspired and accomplishes the same overall functionality.

As illustrated by Tinsley et al, morphological matrices can be used to analyze the similarities or differences between two functionally modeled systems [18]. Here the morphological matrix helps compare the solution strategies used by natural systems (or biomimetic systems) to those used by conventional engineering systems to accomplish similar goals. The morphological matrix framework used to perform this analysis is presented in the Figure 8 below.

Function-Flow Pairs		Primary Functionality	Components	
Natural/Biomimetic Solution	**Conventional Engineered Solution**		**Natural/Biomimetic Solution**	**Conventional Engineered Solution**
Natural System/Inspired Product Flow 1	Conventional Product Flow 1	Function 1	Natural/Inspired Component 1	Conventional Component 1
Natural System/Inspired Product Flow 2	Conventional Product Flow 2	Function 2	Natural/Inspired Component 2	Conventional Component 2
Natural System/Inspired Product Flow 3	Conventional Product Flow 3	Function 3	Natural/Inspired Component 3	Conventional Component 3

Continue for all functions ⇩

Figure 8: Morph matrix template to be used for comparative analysis

For a biomimetic product pair, the morphological matrix is used to compare the bio-inspired engineering product with its corresponding conventional product (if it exists). Similarly, when analyzing a natural system with a potential engineering application, the natural system is compared to its corresponding conventional product if it exists.

To help with the comparison, this research defines two changes a designer must look for while analyzing the morphological matrix.

1. Solution Approach Change: A change in the strategy used to achieve the same function
2. Functional Change: An addition or deletion of functions

Each function-flow pair of the morphological matrix under analysis must be reviewed to identify whether either of the defined changes describe it. Once each function flow pair is reviewed, all the identified changes must be noted by 'Change type' for use in step 6. Also, for each change type the characteristic difference in terms of strategy, behavior, and/or function between the conventional and natural/biomimetic product is identified and noted.

The next step in analyzing the products and/or system involves asking questions of the functional models using the theory of highly optimized tolerance and the FBS knowledge representation scheme.

3.2.5 Step 5: Questioning the Functional Models Using the Theory of Highly Optimized Tolerance (HOT Theory) and the Function-Behavior-Structure Representation

To successfully accomplish the subsequent analysis, a thorough review and understanding of the system or product's functional model and working within its defined scope is essential. Recall, that the specific inspired (in the case of a bio-inspired system) or inspiring (in the case of a natural system) features and aspects determine the functional model's scope and scale.

To ensure an effective and comprehensive review of the biomimetic product pair or natural system, the method outlines the following steps for the user.

1. Understanding the definition of a HOT characteristic.
2. Using the FBS representation in the context of the HOT theory to question the functional models to ascertain underlying HOT characteristics of the biomimetic product pair or natural system.

The first step establishes the context within which the analysis is to be performed. This context is set up by understanding the theory of highly optimized tolerance and in turn defining the term, HOT characteristic. The theory suggests that highly interconnected, non-self similar complex systems are robust in the face of anticipated and 'designed-for' conditions; yet fragile against unexpected events. Essentially, the inherent characteristics and structure of such products make them desirably robust. With this in mind, the definition of a HOT characteristic is formulated as below.

- <u>HOT characteristics</u>: A product or system's characteristics that make it highly optimized, robust, and tolerant to 'designed-for' environmental conditions.

Here, it is key to understand that the complex system or product's features, functional elements, structures, strategies, and/or behaviors make it robust to the designed-for environment. These are what we are looking to infer from the analysis. The term 'designed-for' environment implies that the product or system's performance in unexpected conditions or unforeseen environmental circumstances won't be considered during the subsequent review.

Having established the definition of a HOT characteristic, it can now be used to ask specific systems level and/or parts level questions of the product or system. The answers to these questions are HOT characteristics that identify the inherent bio-inspired sub-functions, features, structures, strategies, and behaviors. These are then abstracted into biomimetic design principles.

Function, behavior, and structure form a commonly used knowledge representation scheme in conceptual design. This representation scheme captures the essence of a system in abstract terminology. Here, the developed questions leverage this scheme to effectively extract the HOT characteristics of the product or system. In other words, the questions investigate the natural system or biomimetic product pair in terms for its function, behavior, and structure. The four questions to be asked of the product or system are listed below.

a. What features/characteristics of the product or system make it robust (as in ensures the successful accomplishment of its overall) in terms of functionality within the 'designed-for' environment?
b. What features/characteristics of the product or system's architecture/structure make it robust to its 'designed-for' environment?
c. What features/characteristics of the product or system's strategy/behavior optimize its performance within the 'designed-for' environment?
d. How does the product or system ensure effectively achieving its overall objective?

As previously noted, these questions must be asked at the systems level and/or parts level. Specifically, the answers to the questions highlight the features, functional elements, structures, strategies, and/or behaviors that make the natural system or bio-inspired system robust in terms of achieving its functionalities.

In the case where a biomimetic product pair is to be analyzed, the questions are asked of the bio-inspired engineering product. It is also important to consciously keep in mind a comparison to the conventional product (as a baseline) and thereby answer the questions in the context of this comparison. Thus, the answers highlight the bio-inspired product's advantageous features, functional elements, strategies, and/or behaviors.

On the other hand, for a natural system under analysis, the questions are asked of the natural system itself. Again, they are answered within the context of a comparison with the conventional product. The resulting answers highlight the natural system's advantageous features, functional elements, strategies, and/or behaviors.

In must be noted that in the absence of a comparative conventional product, the stated questions can still be answered and the required underlying characteristics can be inferred from the bio-inspired product or natural system. However, in the absence of a comparative product the underlying characteristics might not be easily apparent and therefore additional time and effort might be required to effectively infer the requisite characteristics.

3.2.6 Step 6: Categorization of HOT Characteristics and Principle Abstraction

The identified characteristics from each of the products or systems analyzed may vary in hierarchy, scope, and type. Developing biomimetic design principles by abstracting these characteristics is an inherently subjective process. To ensure the effectiveness of the proposed abstraction, this research adds structure to the process and lays out guidelines for biomimetic design principles. This structure is adapted from a similar abstraction process used by Singh et al to develop transformation principles [36]. The four steps involved in abstracting the identified characteristics into biomimetic design principles are described below.

Step 1: Listing and reviewing all the characteristics identified for each biomimetic product pair and/or natural system

For each natural system or biomimetic product pair, separately list all the characteristics identified from the morphological matrix comparison or the HOT theory questioning. Review the list for characteristics that highlight the same feature, structure, strategy, and/or behavior. Any duplicate characteristics identified from the same biomimetic product pair or natural system must be eliminated.

Step 2: Using color-coding to group the identified characteristics of all the biomimetic product pairs and natural systems

The characteristics are color-coded based on common features, functional elements, structures, strategies, and/or behaviors observed at the systems level and/or parts level. The color-coded tagging offers a simple yet powerful visual representation that helps make the iterative process of sorting and grouping the large number of varied characteristics easier.

The characteristics inferred from all the biomimetic product pairs and natural systems analyzed are reviewed individually. A new group is started every time two similar characteristics (in terms of the features, structures, and/or behavior they refer to) are identified. Each group is assigned a different color and all similar characteristics identified subsequently are tagged with that color. For example consider the following characteristics.

a. The inchworm inspired actuator eliminates the need for transformations between non-linear and linear motion with the use of a composite structure: flexibly body with clamps at each end.
b. The gecko inspired adhesive tape consists of nano-scaled hair like structures attached in a grid like pattern on a smooth and flexible tape.
c. The Namibian beetle inspired material used to collect water is a composite made out of hydrophilic peaks and hydrophobic lowlands.
d. The composite (rigid foam sandwiched by keratin protein) structure gives the toucan beak its lightweight and high strength.
e. The Nacre inspired composite's (Aluminum oxide and polymethyl methacrylate) internal structure gives it a toughness that is 300 times greater than that of its constituents.

These characteristics are grouped based on the observation that in each case the structure is made up of different parts with distinct material properties. The constituent elements interact at a parts level or macro-level and not the molecular level (commonly associated with reference to modern composites).

Additionally, sometimes the same characteristic might fall under more than one group. In such cases the same characteristic is tagged with the colors of all the groups it falls under. Consider the following characteristic: The gecko inspired tape consists of nano-scaled self-similar hair like microstructures attached to a smooth flexible tape to ensure adhesion redundancy. As seen above, this alludes to using different parts (i.e. the hair like microstructures for attachment and the smooth flexible tape for support) with distinct properties. However, another group that this characteristic falls under suggests using numerous instances of a single feature (i.e. the hair-like microstructures arranged in a grid pattern). Therefore, this characteristic is tagged with colors of both the groups.

Step 3: Defining the principles using a universal criteria

This step involves reviewing the characteristics within each of the groups (identified in the earlier steps) and developing a principle that effectively represents them. To formulate the required principles, this research outlines the criteria for a biomimetic design principle.

1. A principle must describe a high-level system strategy, behavior, or functionality.
    a. Describes observable biologically inspired phenomenon that achieves some expected purpose.
    b. Does not describe component level attributes like material selections and chemical compositions.

c. Stated in useful and high-level abstract terms to avoid fixation on particular solutions.

2. A principle must be domain independent
3. All developed principles must be exclusive of each other in their descriptions of system strategies, behaviors, or functionalities.
4. Each principle must be accompanied with up to two facilitators that help the designer effectively use each principle for inspiration. It can be accompanied with a visual illustration.

For example, the following principles are formulated to describe the two groups identified from the gecko inspired adhesive tape:

Products structures with different parts → *Make single part from two or more parts with distinct material properties and functionalities*

Numerous instances of a single feature → *Substitute discrete self-similar features in place of a single feature used to achieve a critical function*

The principles are stated in useful yet abstract terms to guide the designer towards a certain line of thought and thereby inspire new solution ideas. They implicitly leverage nature's solution principles and therefore a designer need not have a great deal of biological knowledge.

Step 4: Categorizing the principles into super groups

After sorting and grouping the characteristics identified from a bio-inspired product and natural system review, a design principle was developed to represent each group. In this step, the principles themselves are reviewed and grouped based on similarity using a color-coding scheme similar to that used in step 1. These groups are called super groups to maintain the analogy with the transformation principle abstraction methodology.

The super groups classify the biomimetic design principles based on their solution strategies. Thus each group represents a specific nature inspired solution strategy and is stated in a system level or parts level terminology. By this logic, it is evident that the super groups presented here are not comprehensive. The solution strategy used by a newly identified principle would dictate whether it is added to an existing super group or whether a new super group is created to represent it. The identified super groups and their corresponding principles are listed in Table 2 below.

Table 2: Categorizing the principles into super groups

Super Groups	Principles
Structure	Make single part from two or more parts with distinct material properties and functionalities. Substitute discrete self-similar features in place of a single feature used to achieve a critical function. Adapt the internal structure of a composite material to meet specific functional needs. Use structural features that are physically sensitive to environmental materials and/or flows.
Morphology – Shape or Form	Flow manipulation: Use static or dynamic features to manipulate/guide/control the material or energy flows across the structure to meet functional needs. Adapt and optimize the form/shape/size of the product to meet specific functional needs.
Environmental interaction	Use materials and/or energy from the environment to help the product /system accomplish its function. Use static and/or dynamic structures to replicate (or substitute) the natural environment that optimizes the product/system's performance.
Function manipulation	Multi-functionality: Make the same part perform two or more distinct functions. Prevention over correction: Build preventive functionality into the product/system in place of reactive or corrective functionality to help achieve an overall function.

The categorization into super groups serves two main purposes. First, the super groups guide the designer in using the biomimetic design principles. The super groups direct the designer to specific principles based on the design problem’s attributes. These could include specific needs of a design problem’s solution or specific constraints on the design problem. For example, if a design problem requires the designer not to change the shape and form of the product; then the super group ‘Morphology – Shape or Form’ can be eliminated from the review.

Second, the super groups serve as a guideline to extracting additional biomimetic design principles. One way is to look for more principles for super groups that have few principles. Another and possibly more important use it to find principles for super groups not yet identified from the existing principles. These new super groups can expand the domains covered by the biomimetic principles through needs identified during the design process.

4 APPLYING THE PRINCIPLE EXTRACTION METHODOLOGY

The previous subsection described the developed principle extraction methodology in detail. To help better understand the methodology and also support its validation, the following subsection illustrates using the methodology to extract biomimetic design principles from an example biomimetic product pair. Each step is detailed below using a common example.

4.1 Step 1: Identify Appropriate Biomimetic Product Pair or Natural System

The example chosen here is the gecko inspired adhesive tape. Shown in Figure 9 below, is an adhesive tape inspired by the gecko feet's ability to attach to external surfaces.

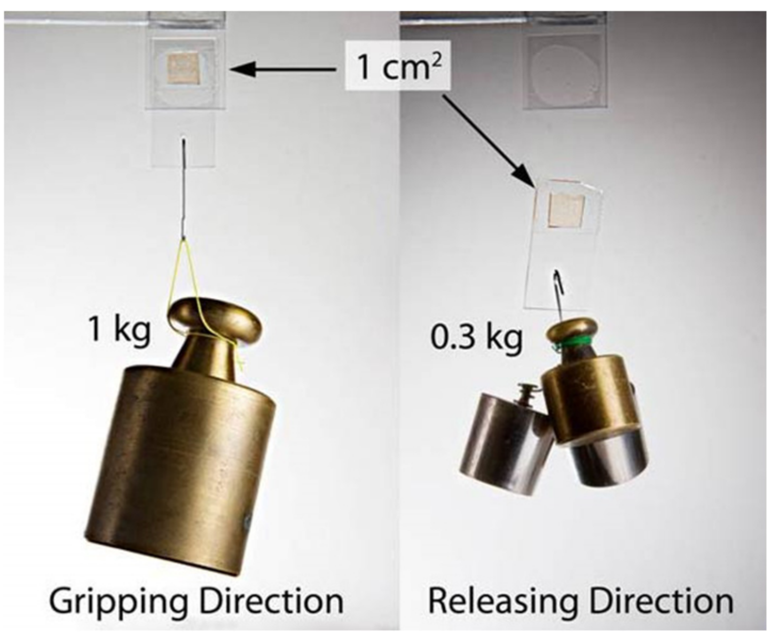


Figure 9: The gecko inspired synthetic tape with hair-like microstructures is adhesive, reusable, and self-cleaning (Photo: NanoRobotics Laboratory, Carnegie Mellon University [47])

4.2 Step 2: Determine Natural System, Bio-inspired Engineering Product, and/or Conventional Product

The methodology requires identifying the natural system, bio-inspired product, and corresponding conventional product for the example biomimetic product pair: gecko feet's attachment mechanism and gecko inspired adhesive tape. These are identified and described below.

- Natural system: Gecko feet's attachment mechanism

The gecko foot's ability to attach to external surfaces has been attributed to van der Waals attraction forces. A gecko's foot consists of an array of slender microstructures called setae. Each setae of the gecko braches into 100-1000 hair-like tips called spatulae, as seen Figure 10E below.

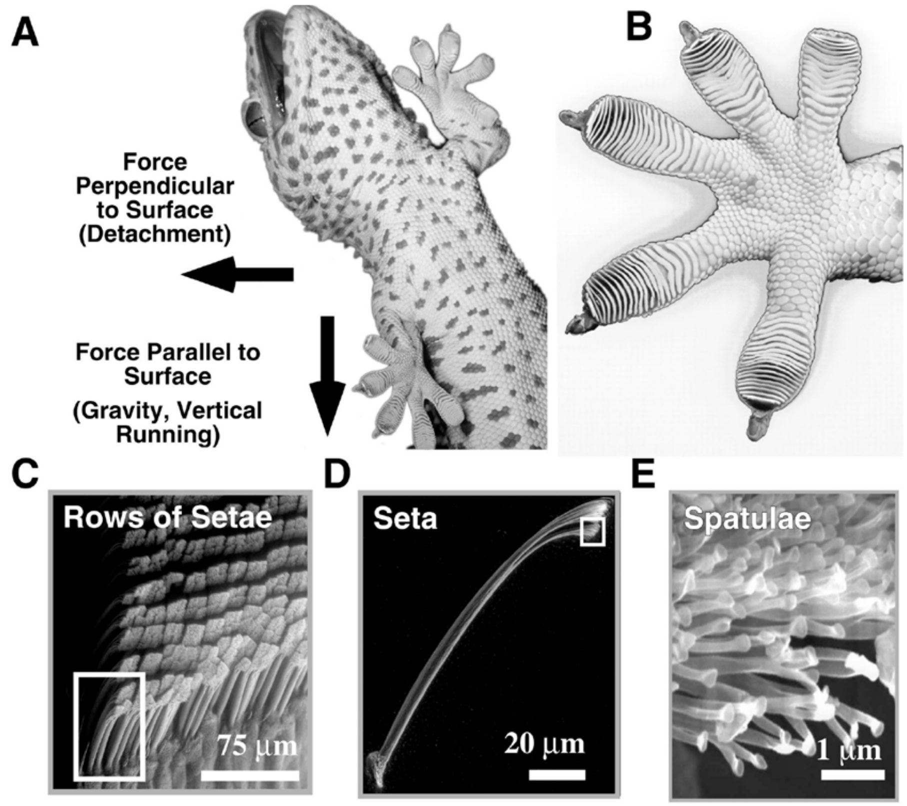


Figure 10: The gecko foot's surface structure facilitates adhesion to external surfaces as adapted from [48]

The size and shape of these tips facilitate intimate contact with the external surface and enable attraction towards external surfaces [49]. This proximity of the tips to the exterior surface results in or engages intermolecular van der Waals attraction forces. The arrangement of the spatular tips and setae also allow for directional adhesion and self-cleaning. This simple mechanism is robust to surface type, chemistry, wetness, and other environmental conditions.

- Bio-inspired product: Gecko inspired adhesive tape

Dry adhesives inspired by the gecko foot's hair-like structures have varied possible applications in robotics and fastening. Experimental research has led to the development of numerous different adhesive pads and tapes using different manufacturing techniques. Despite different methods and technologies the basic criteria includes the presence of many nanoscale hair like structures arranged in a grid like pattern. Figure 11 and Figure 12 below show a gecko inspired adhesive pad and patch that consist of nano-scale conical pillars [50] or propylene microfiber array [51].

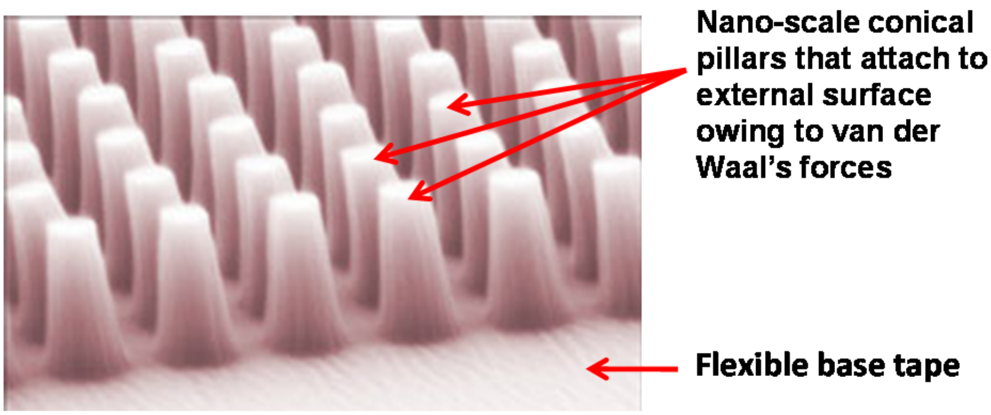


Figure 11: Nano-scale conical pillars on the pad attach to external surfaces owing to van der Waals forces [50]

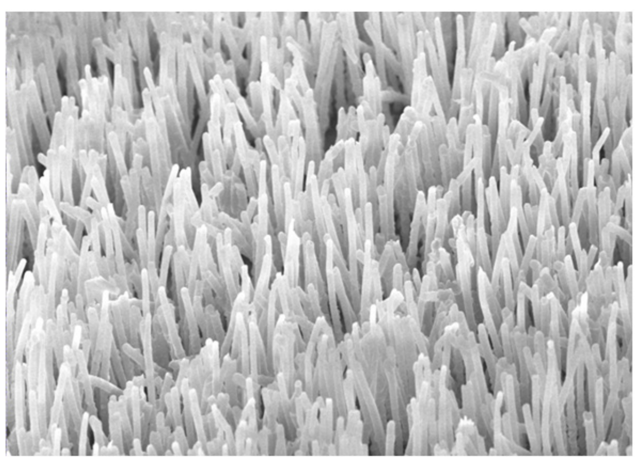


Figure 12: The gecko inspired patch is covered with 15-20 micrometer long and 0.6 micrometer diameter fibers attach to external surfaces owing to van der Waals forces [51]

Unlike conventional adhesive tapes, the gecko inspired tape is reusable. Other robust properties include its directionality and dry attachment characteristics.

- Conventional product: Adhesive tape

There are many devices that provide the gecko inspired tape's attachment function. However, the appropriate comparative conventional product considered here is a traditional adhesive tape. Like the gecko inspired tape, it is flexible and has one side that attaches to an external surface.

4.3 Step 3: Functional Modeling

As shown above, the chosen example is a biomimetic product pair. Therefore, a functional model for the bio-inspired engineering product and a functional model for the conventional engineering product are developed. First, the design question or problem solved by the proposed bio-inspired engineering product is identified as follows: *Design a product that attaches to and detaches from any external surface as and when required to do so.*

The gecko inspired adhesive tape is functionally modeled at the organism scale, since the inspiration is drawn at that biological scale. A functional model for the gecko inspired adhesive tape is presented in Figure 13 below.

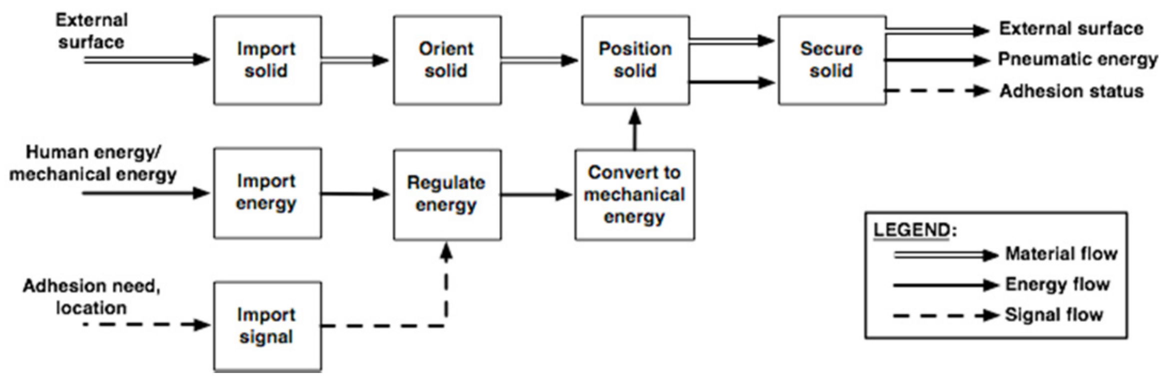


Figure 13: Functional model for bio-inspired product: gecko inspired adhesive tape

Similarly the functional model for a conventional adhesive tape is presented in Figure 14 below.

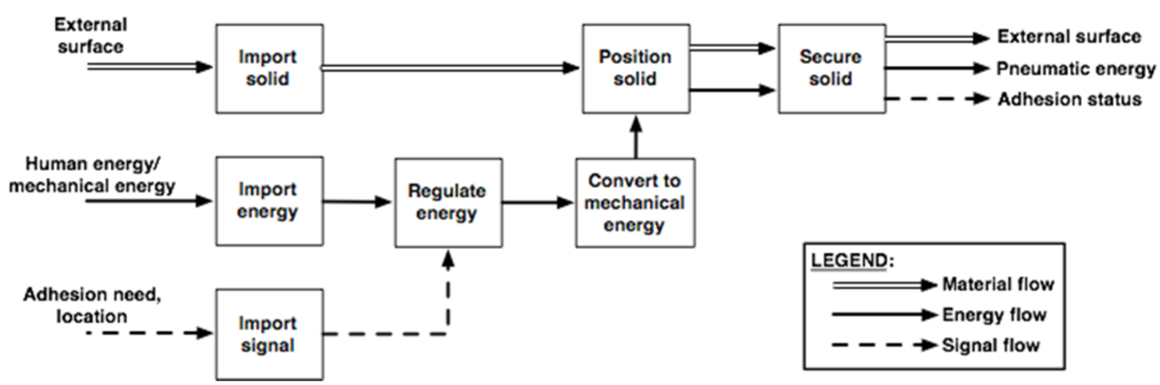


Figure 14: Functional model for conventional product: conventional adhesive tape

The functional models for the bio-inspired product (or gecko tape) and the conventional engineering product (or the conventional adhesive tape) are quite similar. This is due to the similar needs or objectives they fulfill.

An example of such a pair is bio-inspired robot sensing/navigation system and its corresponding conventional navigation system. Unlike a conventional system, the moth's eye inspired system does not use a visual sensor with directional and focus controls. Rather it uses a simple wide field of view (to eliminate the direction control) and color contrast (to eliminate focusing of specific objects in field of view) strategy. Therefore, they use different strategies or sub-functions to achieve the same overall function.

4.4 Step 4: Morphological Matrices

Having developed the requisite functional models, the next step is to compare the strategies used by the bio-inspired system (or natural system) to those used by the conventional system to accomplish similar objectives. The morphological matrix uses the function-flow pairs and component breakdown to accomplish this comparison as seen in Table 3 below.

Table 3: The morphological matrix helps compare the bio-inspired and conventional products' function-flow pairs

Function-Flow Pairs		**Primary Functionality**	**Components**	
Natural/Biomimetic Solution	**Conventional Engineered Solution**		**Natural/Biomimetic Solution**	**Conventional Engineered Solution**
Import solid (external surface)	Import solid (external surface)	Import	Hand/robotic arm	Hand/arm
Orient solid (with respect to tape's nanostructures)	X	Orient	Hand/robotic arm and nanostructure fiber's direction	X
Import human/mechanical energy	Import human/mechanical energy	Import	Hand/robotic arm	Hand/arm
Regulate energy	Regulate energy	Regulate	Hand/robotic arm	Hand/arm
Convert to mechanical energy	Convert to mechanical energy	Convert	Hand/robotic arm	Hand/arm
Import signal	Import signal	Import	Brain/circuit board	Brain/circuit board
Position solid	Position solid	Position	Hand/ robotic arm	Hand/arm
Secure solid	Secure solid	Secure	Nano-scale fibers	Chemical coating

The methodology requires identifying any functional or solution approach changes between the functional models using the morphological matrix. In the table above, the red colored font identifies a functional change and the blue colored font identifies a solution approach change as required.

Functional Change: Orient

The sub-function 'orient solid' is observed in the biomimetic adhesive tape's functional model but not in the conventional adhesive tape's functional model. In this context, an additional 'orient solid' function refers to the directionality of the arrayed nano-scale fibers on the biomimetic tape's surface. The nano-scale fibers must be oriented in a certain way with respect to the external surface initiate attachment, while changing the orientation results in detachment. Comparing this to the conventional tape, helps identify the characteristic difference: *The orientation/arrangement or the nano-scale hair-like fibers on the gecko inspired tape make it directional.*

Solution Approach Change: Secure

Both the conventional tape and the gecko inspired tape both use different strategies to accomplish the same 'secure solid' function. While a conventional tape uses a chemical coating, the gecko inspired tape uses an array of nano-scale hair like fibrous microstructures to attach to an external surface owing to van der Waals forces. This comparison suggests the following characteristic difference: *Use numerous fibers (or hair-like structures) to leverage van der Waal's attraction forces by increasing proximity to the external surface.*

4.5 Step 5: Questioning the Functional Models Using the Theory of Highly Optimized Tolerance and the Function-Behavior-Structure Representation

This step involves questioning the functional models within the context of the theory of highly optimized tolerance. Each question and its identified answers for the gecko inspired tape are presented below.

a. What features/characteristics of the product or system make it robust (as in ensures the successful accomplishment of its overall) in terms of functionality within the 'designed-for' environment?

- *The gecko inspired tape's numerous self-similar hair-like microstructures ensure adhesion redundancy.*

For the gecko inspired tape, 'robustness in terms of functionality' refers to its adhesion redundancy. The numerous fibers (or hair-like structures) on the tape's surface ensure redundancy.

b. What features/characteristics of the product or system's architecture/structure make it robust to its 'designed-for' environment?

- *The form, shape, and arrangement of the nano-scale hair like structures on the gecko inspired tape make it directional.*
- *The gecko inspired tape consists of nano-scale hair like structures attached in a grid pattern on a smooth and flexible tape.*

With regards to its structural configuration two characteristics are apparent in the gecko inspired tape's design. First, the tape's specific arrangement and design of the nano-scale fibers allows for directional adhesion. This characteristic was also inferred from the morphological matrix comparison. Second, the tape comprises of two different parts: the flexible base/tape and the fibers (or hair-like structures) arranged on its surface.

c. What features/characteristics of the product or system's strategy/behavior optimize its performance within the 'designed-for' environment?

- *The nano-scale hair-like structures on the gecko inspired tape facilitate adhesion as well as self-cleaning.*

An optimal design must perform well in all possible environmental conditions it is designed to work in. In this context, the term optimal suggests the tape should attach to any surface. Therefore, the tape's attachment ability must not be hindered by surface type, structure, and quality. The bio-inspired tape's strategy is to use the hair-like structures to ensure attachment while using them to overcome the presence of dirt particles on various surface types.

d. How does the product or system ensure effectively achieving its overall objective?

- The gecko inspired tape uses the external surface (along with its fibrous structures) to keep itself clean and re-usable.

To ensure effective attachment to the external surface, the tape must avoid damage in terms of the presence of dirt particles on it. It achieves this by using the external surface to attract any dirt particles that could potentially stick to it.

4.6 Step 6: Categorization of HOT Characteristics and Principle Abstraction

This step outlines the procedure used to abstract the identified characteristics into biomimetic design principles. The first step in this abstraction process requires eliminating duplicate characteristics identified from the same biomimetic product pair or natural system.

For the gecko inspired tape, the characteristics identified using the morphological matrix comparison and the HOT theory questions are listed below.

1. The orientation/arrangement or the nano-scale hair-like fibers on the gecko inspired tape make it directional.
2. Use numerous fibers (or hair-like structures) to leverage van der Waal’s attraction forces by increasing proximity to the external surface.
3. The gecko inspired tape's numerous self-similar hair-like microstructures ensure adhesion redundancy.
4. The form, shape, and arrangement of the nano-scale hair like structures on the gecko inspired tape make it directional.
5. The gecko inspired tape consists of nano-scale hair like structures attached in a grid pattern on a smooth and flexible tape.
6. The nano-scale hair-like structures on the gecko inspired tape facilitate adhesion as well as self-cleaning.
7. The Gecko inspired tape uses the external surface (along with its fibrous structures) to keep itself clean and re-usable.

However, a quick review results in the elimination of two duplicate characteristics.

1. The gecko inspired tape's numerous self-similar hair-like microstructures ensure adhesion redundancy.
2. The form, shape, and arrangement of the nano-scale hair like structures on the gecko inspired tape make it directional.
3. The gecko inspired tape consists of nano-scale hair like structures attached in a grid pattern on a smooth and flexible tape.
4. The nano-scale hair-like structures on the gecko inspired tape facilitate adhesion as well as self-cleaning.
5. The Gecko inspired tape uses the external surface (along with its fibrous structures) to keep itself clean and re-usable.

Steps 2, 3, and 4 involve reviewing characteristics identified from all the biomimetic product pairs and natural systems reviewed. This review process abstracts the characteristics into high-level biomimetic design principles. Therefore, the following part of this subsection includes the principles identified from all the biomimetic product pairs and natural systems reviewed.

Step 2: Using color-coding to group the identified characteristics of all the biomimetic product pairs and natural systems

All the identified characteristics are color-coded and then grouped based on common features, functional elements, structures, strategies, and/or behaviors observed at the system and/or parts level. All the similar characteristics must be grouped together. Table 4 below shows the different groupings of the principles identified.

Table 4: Similar characteristics grouped based on commonalities

Groups of similar characteristics
1. The inchworm inspired actuator eliminates the need for transformations between non-linear and linear motion with the use of a composite structure: flexible body with clamps at each end. 2. The gecko inspired tape consists of nano-scale hair like structures attached in a grid pattern on a smooth and flexible tape. 3. The Namibian beetle inspired material used to collect water is a composite made out of hydrophilic peaks and burled hydrophobic lowlands. 4. The composite (rigid foam sandwiched by keratin protein) structure gives the toucan beak its lightweight and high strength. 5. The Nacre inspired composite's (Aluminum oxide and polymethyl methacrylate) internal structure gives it a toughness that is 300 times greater that that of its constituents. 6. The Scarabei cuticle is a composite structure with chitin-fibers and sclerous protein matrices.

Table 4 continued

Groups of similar characteristics
1. The shape and size of the micro-structural bumps are optimized to guide and manipulate the incident light to eliminate reflection. 2. The nose's optimized shape manipulates air flowing over it to reduce air pressure accumulation. 3. The rough surface texture manipulates the water flowing over the suit to reduce drag. 4. The blades' toothed (troughs and tubercles) leading edge design guides and manipulates the airflow over its surface. 5. The shape of the edges on the pantograph is optimized to create smaller vortices in the airflow that in turn help with noise regulation. 6. The dynamic IMOD element's air cavity is controlled to manipulate the wavelength (color) of the light reflected by it. 7. The shape of the car is optimized to reduce air drag coefficient leading to higher efficiency. 8. The ground beetle inspired rough surface morphology minimizes soil adhesion of the soil-engaging component.
1. The moth eye inspired anti-glare surface uses discrete and self-similar micro-structural bumps to manipulate the incident light and eliminate reflection. 2. The cricket inspired flow sensor's array of hair-like fibrous structures ensures sensing redundancy. 3. The gecko inspired tape's numerous self-similar hair-like microstructures ensure adhesion redundancy. 4. The lotus inspired self-cleaning surface is covered with discrete ridged nano-scale protrusions to prevent the accumulation of dirt particles between the ridges. 5. Velcro's array of discrete hooks ensures mating redundancy to a fibrous strap. 6. The discrete denticles (scales) on the shark's skin reduce drag. 7. The water harvesting material consists of discrete hydrophilic peaks to enhance the water collection volume. 8. The whale flipper inspired windmill blades' leading edge consists of discrete peaks and troughs (toothed edge). 9. The numerous serrated edges manipulate the air flowing across the Shinkansen train pantograph to ensure lower noise levels. 10. The butterfly wing inspired Mirasol display is made up of numerous IMOD elements arranged in a grid to generate a color picture or video. 11. The biomimetic soil engaging components' surface is covered with discrete convex bumps that reduce the affinity between the soil and the surface.
1. The Eastgate Complex integrates the internal and external environments reducing the chances of system failure. 2. The Gecko inspired tape uses the external surface (along with its fibrous structures) to keep itself clean and re-usable. 3. The lotus uses water flowing over it (along with its surface structure) to prevent unwanted dirt particles form adhering to its surface. 4. The cocklebur plant's seeds leverage the surrounding environment (animals with fur, birds with feathers) for dispersal. 5. The shark uses the water flowing along its surface (along with it ribbed denticles) to keep its skin clean. 6. Owing to its shape, the beetle inspired water harvesting system leverages gravity to direct water flow and ensure energy efficient collection.

Table 4 continued

Groups of similar characteristics
1. The concrete floors serve as an energy source (passive cooling: thermal energy exchange with air drawn from the exterior) in the termite mound inspired Eastgate Building. 2. Velcro: Using a dedicated fibrous mating strap optimized to attach to the designed hooks ensures the hooks' ability to achieve their function.
1. Shape and size of the cricket inspired flow sensor's mechano-receptive hair allows for higher sensitivities. 2. The form, shape, and arrangement of the nanoscale hair like structures on the gecko inspired tape can make the tape directional. 3. Velcro: The shape and size of the hooks are optimized to attach to the fibrous strap. 4. The water harvesting material's hydrophilic peaks attract water from the fog collecting it in droplets which then 'roll' down over a shaped hydrophobic region. 5. The ground beetle inspired rough surface morphology minimizes soil adhesion of the soil-engaging component.
1. The nanoscale hair like structures on the gecko inspired tape facilitates adhesion as well as self-cleaning. 2. The sharkskin’s dermal denticles (ridged scales) reduce drag by manipulating the water flow over it as well as keep the skin clean due to their structure and shape.
1. The Shinkansen train's nose prevents the development of large pressure vortices and avoids the need for noise cancellation devices. 2. An important part of the lotus inspired surface's strategy is to prevent the accumulation of dirt rather than react after the dirt has been accumulated. 3. The shark's dermal denticles prevent dirt particles from adhering to the skin. 4. The Shinkansen train's owl inspired serrated pantograph design prevents the generation of large air vortices and avoids the need for noise cancellation devices. 5. An important part of the ground beetle's strategy is to prevent soil adhesion rather than react after the soil has already adhered to the surface.
1. Plant abscission inspired micro-assembly procedure uses an intermediate part to separate two objects (Micro-screw and propylene rod).
1. The sandwich structure of a rigid foam and keratin layers makes the toucan beak lightweight and strong. 2. The abalone shell inspired highly ordered layered structure of constituents (Aluminum oxide and polymethyle methacrylate) result in high fracture toughness and yield strength. 3. The tumblebug cuticle's internal structural arrangement and layout of fibers is the key to the increased rupture strength for composites with holes in the structure. 4. The helicoidal structure of chitin-fiber layers and sclerous protein matrices provides the scarabei cuticle its high fracture toughness.
1. The sensory hairs deform (physically) under the influence of external stimuli (airflow). This deformation is detected and captured by the cells. 2. The optimally located holes in the insect cuticle deform under external stimuli. Cells detect this deformation.

Step 3: Defining the principles using a universal criteria

The individual groups of characteristics are reviewed and a principle is formulated to describe each group. Each principle must highlight the system or parts level features, functional elements, structures, strategies, and/or behaviors implied by the characteristics within the individual group. Table 5 lists the high-level biomimetic design principles and the corresponding groups of characteristics.

Table 5: Biomimetic design principles formulated to each group of characteristics

Groups of similar characteristics	Biomimetic Design Principles
1. The inchworm inspired actuator eliminates the need for transformations between non-linear and linear motion with the use of a composite structure: flexible body with clamps at each end. 2. The gecko inspired tape consists of nano-scale hair like structures attached in a grid pattern on a smooth and flexible tape. 3. The Namibian beetle inspired material used to collect water is a composite made out of hydrophilic peaks and burled hydrophobic lowlands. 4. The composite (rigid foam sandwiched by keratin protein) structure gives the toucan beak its lightweight and high strength. 5. The Nacre inspired composite's (Aluminum oxide and polymethyl methacrylate) internal structure gives it a toughness that is 300 times greater than that of its constituents. 6. The scarabei cuticle is a composite structure with chitin-fibers and sclerous protein matrices.	**Composite: Make single part from two or more parts with distinct material properties and functionalities.**
1. The shape and size of the micro-structural bumps are optimized to guide and manipulate the incident light to eliminate reflection. 2. The nose's optimized shape manipulates air flowing over it to reduce air pressure accumulation. 3. The rough surface texture manipulates the water flowing over the suit to reduce drag. 4. The blades' toothed (troughs and tubercles) leading edge design guides and manipulates the airflow over its surface. 5. The shape of the edges on the pantograph is optimized to create smaller vortices in the airflow that in turn help with noise regulation. 6. The dynamic IMOD element's air cavity is controlled to manipulate the wavelength (color) of the light reflected by it. 7. The shape of the car is optimized to reduce air drag coefficient leading to higher efficiency. 8. The ground beetle inspired rough surface morphology minimizes soil adhesion of the soil-engaging component.	**Flow manipulation: Use static or dynamic features to manipulate/guide/control the material or energy flows across the structure to meet functional needs.**

Table 5 continued

Groups of similar characteristics	Biomimetic Design Principles
1. The moth eye inspired anti-glare surface uses discrete and self-similar micro-structural bumps to manipulate the incident light and eliminate reflection. 2. The cricket inspired flow sensor's array of hair-like fibrous structures ensures sensing redundancy. 3. The gecko inspired tape's numerous self-similar hair-like microstructures ensure adhesion redundancy. 4. The lotus inspired self-cleaning surface is covered with discrete ridged nano-scale protrusions to prevent the accumulation of dirt particles between the ridges. 5. Velcro's array of discrete hooks ensures mating redundancy to a fibrous strap. 6. The discrete denticles (scales) on the shark's skin reduce drag. 7. The water harvesting material consists of discrete hydrophilic peaks to enhance the water collection volume. 8. The whale flipper inspired windmill blades' leading edge consists of discrete peaks and troughs (toothed edge). 9. The numerous serrated edges manipulate the air flowing across the Shinkansen train pantograph to ensure lower noise levels. 10. The butterfly wing inspired Mirasol display is made up of numerous IMOD elements arranged in a grid to generate a color picture or video. 11. The biomimetic soil engaging components' surface is covered with discrete convex bumps that reduce the affinity between the soil and the surface.	**Substitute discrete self-similar features in place of a single feature used to achieve a critical function.**
1. The Eastgate Complex integrates the internal and external environments reducing the chances of system failure. 2. The Gecko inspired tape uses the external surface (along with its fibrous structures) to keep itself clean and re-usable. 3. The lotus uses water flowing over it (along with its surface structure) to prevent unwanted dirt particles form adhering to its surface. 4. The cocklebur plant's seeds leverage the surrounding environment (animals with fur, birds with feathers) for dispersal. 5. The shark uses the water flowing along its surface (along with it ribbed denticles) to keep its skin clean. 6. Owing to its shape, the beetle inspired water harvesting system leverages gravity to direct water flow and ensure energy efficient collection.	**Use materials and/or energy from the environment to help the product/system accomplish its function.**
1. The concrete floors serve as an energy source (passive cooling: thermal energy exchange with air drawn from the exterior) in the termite mound inspired Eastgate Building. 2. Velcro: Using a dedicated fibrous mating strap optimized to attach to the designed hooks ensures the hooks' ability to achieve their function.	**Use static and/or dynamic structures to replicate (or substitute) the natural environment that optimizes the product/system's performance.**

Table 5 continued

Groups of similar characteristics	Biomimetic Design Principles
1. Shape and size of the cricket inspired flow sensor's mechano-receptive hair allows for higher sensitivities. 2. The form, shape, and arrangement of the nano-scale hair like structures on the gecko inspired tape make the tape directional. 3. Velcro: The shape and size of the hooks are optimized to attach to the fibrous strap. 4. The water harvesting material's hydrophilic peaks attract water from the fog collecting it in droplets which then 'roll' down over a shaped hydrophobic region. 5. The ground beetle inspired rough surface morphology minimizes soil adhesion of the soil-engaging component.	**Form: Adapt and optimize the form/shape/size of the product to meet specific functional needs.**
1. The nanoscale hair like structures on the gecko inspired tape facilitates adhesion as well as self-cleaning. 2. The sharkskin's dermal denticles (ridged scales) reduce drag by manipulating the water flow over it as well as keep the skin clean due to their structure and shape.	**Multi-functionality: Make the same part perform two or more distinct functions.**
1. The Shinkansen train's nose prevents the development of large pressure vortices and avoids the need for noise cancellation devices. 2. An important part of the lotus inspired surface's strategy is to prevent the accumulation of dirt rather than react after the dirt has been accumulated. 3. The shark's dermal denticles prevent dirt particles from adhering to the skin. 4. The Shinkansen train's owl inspired serrated pantograph design prevents the generation of large air vortices and avoids the need for noise cancellation devices. 5. An important part of the ground beetle's strategy is to prevent soil adhesion rather than react after the soil has already adhered to the surface.	**Prevention over correction: Build preventive functionality into the product/system in place of reactive or corrective functionality to help achieve an overall function.**
1. Plant abscission inspired micro-assembly procedure uses an intermediate part to separate two objects (Micro-screw and propylene rod).	**Use part(s) or feature(s) that is sacrificed after its functionality is achieved.**
1. The sandwich structure of a rigid foam and keratin layers makes the toucan beak lightweight and strong. 2. The abalone shell inspired highly ordered layered structure of constituents (Aluminum oxide and polymethyle methacrylate) result in high fracture toughness and yield strength. 3. The tumblebug cuticle's internal structural arrangement and layout of fibers is the key to the increased rupture strength for composites with holes in the structure. 4. The helicoidal structure of chitin-fiber layers and sclerous protein matrices provides the scarabei cuticle its high fracture toughness.	**Adapt the internal structure of a composite material to meet specific functional needs**
1. The sensory hairs deform (physically) under the influence of external stimuli (airflow). This deformation is detected and captured by the cells. 2. The optimally located holes in the insect cuticle deform under external stimuli. Cells detect this deformation.	**Use structural features that are physically sensitive to environmental materials and/or flows**

Step 4: Categorizing the principles into super groups

Having identified the requisite biomimetic design principles, they are then grouped at a high-level. These super groups help with the application of the principles and also serve as a guideline to extracting additional biomimetic design principles. Table 6 presents the biomimetic design principles classified into various super groups.

Table 6: Biomimetic design principles categorized into super groups

Super Groups	**Principles**
Structure	Make single part from two or more parts with distinct material properties and functionalities. Substitute discrete self-similar features in place of a single feature used to achieve a critical function. Adapt the internal structure of a composite material to meet specific functional needs. Use structural features that are physically sensitive to environmental materials and/or flows.
Morphology – Shape or Form	Flow manipulation: Use static or dynamic features to manipulate/guide/control the material or energy flows across the structure to meet functional needs. Adapt and optimize the form/shape/size of the product to meet specific functional needs.
Environmental interaction	Use materials and/or energy from the environment to help the product /system accomplish its function. Use static and/or dynamic structures to replicate (or substitute) the natural environment that optimizes the product/system's performance.
Function manipulation	Multi-functionality: Make the same part perform two or more distinct functions. Prevention over correction: Build preventive functionality into the product/system in place of reactive or corrective functionality to help achieve an overall function. Use part(s) or feature(s) that is sacrificed after its functionality is achieved.

5 STATING AND USING THE DEVELOPED BIOMIMETIC DESIGN PRINCIPLES

The principle extraction methodology is used to analyze 23 biomimetic product pairs and natural systems. This analysis results in the development of biomimetic design principles. They serve as a biomimetic design tool that guides designers toward innovative bio-inspired solutions to engineering problems. More importantly, designers need minimal knowledge of biology or biological terminology to use the developed principles. This is because the abstract high-level design principles inherently leverage nature's solution strategies.

There are two important aspects that help designers effectively leverage the developed principles' potential to inspire innovative designs. The first has to do with how the biomimetic design principles are presented to designers. The second has to do with using the principles themselves. With these in mind, the following subsection describes the method used to present the biomimetic design principles as well as an outline that guides designers in using the principles.

5.1 Stating the Developed Biomimetic Design Principles

To increase its effectiveness in terms of inspiring innovative ideas each principle is stated with up to two facilitators. As defined here, a facilitator is an example inspiration construct that helps the designer in creating bio-inspired solutions using the given principle. These facilitators are constructed from the HOT characteristics used to develop the given principle. In other words, a facilitator is just an example solution that uses the given biomimetic design principle and therefore gives the designer a better understanding of the principle. Table 7 lists two facilitators for each of the developed biomimetic design principles.

Table 7: Biomimetic design principles stated with facilitators

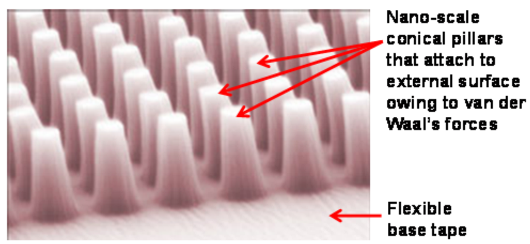
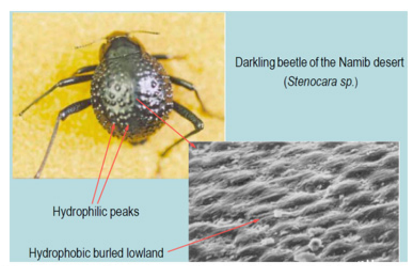
Super Group	Biomimetic Design Principles	Facilitators
Structure	Make single part from two or more parts with distinct material properties and functionalities.	The gecko-inspired adhesive tape uses a composite structure of nano-scaled hair like structures (that attach to an external surface) and a flexible tape (for support) [50].  The Namibian beetle inspired material used to collect water is a composite made out of hydrophilic peaks (that attract moisture from vapor) and hydrophobic lowlands (that guide the collected water droplets towards the mouth).  **The vapor condenses as water droplets on the hydrophilic peaks. The hydrophobic lowlands guide the droplets toward the mouth.**

Table 7 continued

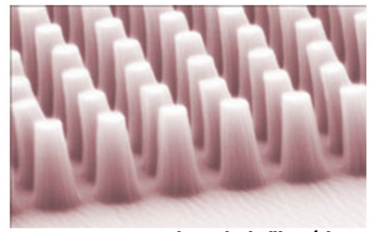
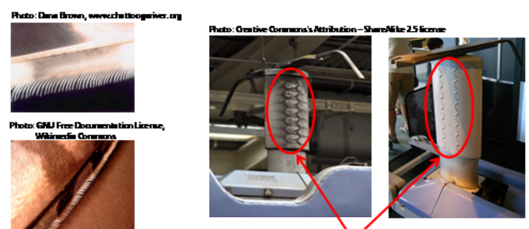
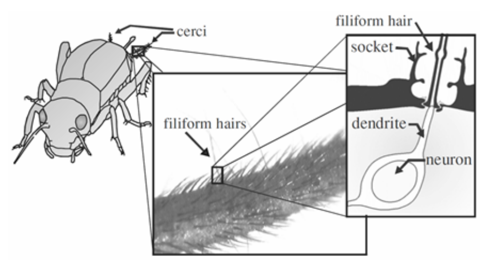
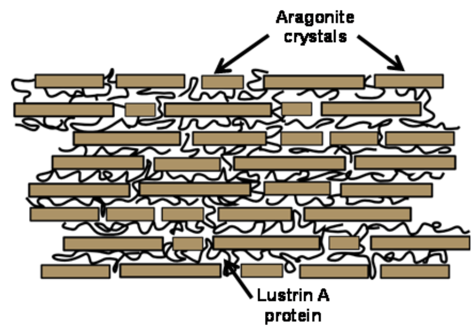
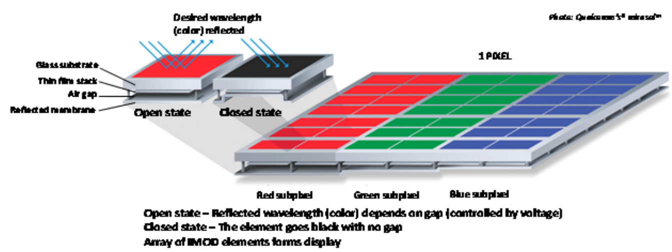
Super Group	Biomimetic Design Principles	Facilitators
Structure	Substitute discrete self-similar features in place of a single feature used to achieve a critical function	The gecko-inspired tape consists of numerous self-similar hair-like microstructures arranged in a grid to improve adhesion redundancy [50].  Numerous nano-scale conical pillars (that attach to external surface owing to van der waals forces) arranged in a grid pattern The Shinkansen train's pantograph uses numerous self-similar serrated edges to manipulate the air flowing across it to lower noise levels.  Serrated edges on owl's flight feathers Serrated edges on the pantograph manipulate airflow across its surface
Structure	Use structural features that are physically sensitive to environmental materials and/or flows.	The cricket's sensory hairs deform (physically) under the influence of external stimuli (airflow). This deformation is detected and captured by the cells.  The filiform hairs on the cerci deform based on airflow around them. This is sensed by the cells at the base of each hair.

Table 7 continued

<table>
<tr><th>Super Group</th><th>Biomimetic Design Principles</th><th>Facilitators</th></tr>
<tr><td>Structure</td><td>Adapt the internal structure of a composite material to meet specific functional needs.</td><td>The abalone shell (or nacre) owes its high strength properties to the optimized composite microstructure of calcium carbonate (in an aragonite crystal form) and Lustrin A protein [52].


</td></tr>
<tr><td>Morphology: Shape or Form</td><td>Use static or dynamic features to manipulate/guide/control the material or energy flows across the structure to meet functional needs.</td><td>The butterfly wing inspired pigment free Mirasol® display uses dynamic IMOD elements (micro-electro-mechanical device) whose air cavity size is desirably changed to manipulate the wavelength (color) of the light reflected by it.



The Shinkansen train's nose shape manipulates the air flowing over it to reduce air pressure accumulation.

Kingfisher beak reduces drag when entering water

The Shinkansen train's nose guides airflow across it</td></tr>
</table>

Table 7 continued

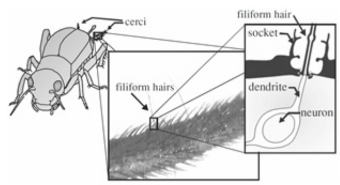
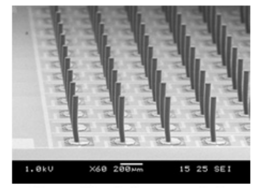
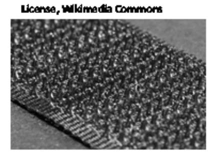
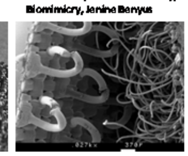
Super Group	Biomimetic Design Principles	Facilitators
Morphology: Shape or Form	Adapt and optimize the form/shape/size of the product to meet specific functional needs.	The shape and size of the cricket inspired flow sensor's mechano-receptive hair like fibers allow for higher sensitivities [53].  **Filiform hairs on he cerci of the cricket senses airflow**  **Array of spiral-suspended sensory hairs** Velcro's hooks are optimally sized and shaped to attach to a fibrous mating strap. Photo: James Clayton, The Conservationist, June 2009  **The cocklebur seed has hooks that attach to animal fur** Photo: GNU Free Documentation License, Wikimedia Commons  Photo: Phillips Exeter Academy, Biomimicry, Janine Benyus  **Velcro hooks are optimally shaped and sized to attach to mating strap**

Table 7 continued

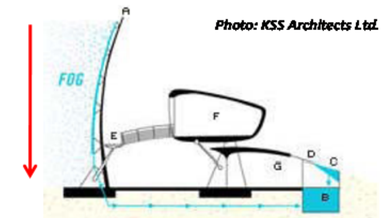
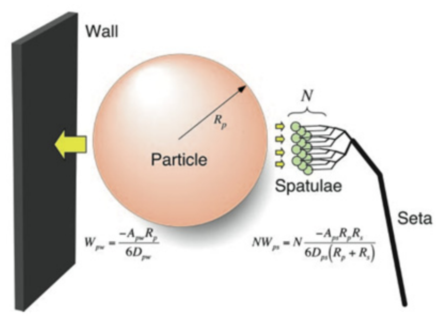
Super Group	Biomimetic Design Principles	Facilitators
Environmental interaction	Use materials and/or energy from the environment to help the product /system accomplish its function.	Owing to its shape, the beetle inspired water harvesting system leverages gravity to direct water flow and ensure energy efficient collection.  **Water droplet collected from fog flow downwards (due to gravity) and into a collector** The gecko inspired adhesive tape uses the external surface (along with its fibrous structures) to prevent unwanted dirt particles from adhering to its surface [54].  **A dirt particle experiences greater Van der Waals attraction from the external wall than the hair-like structures, spatulae (owing to their shape and size) on the gecko's foot.**

Table 7 continued

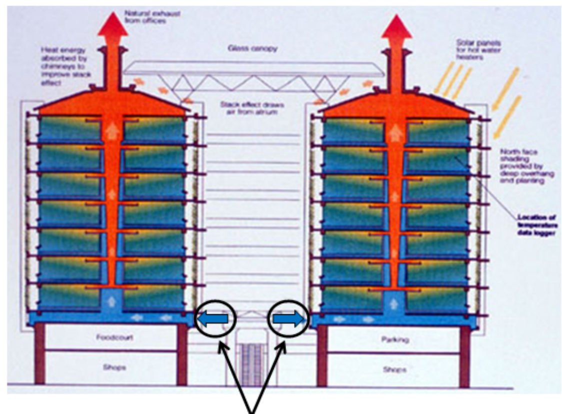
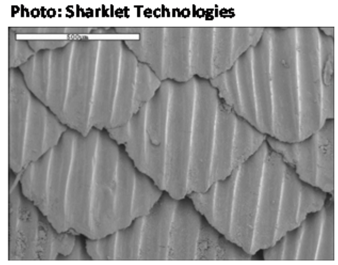
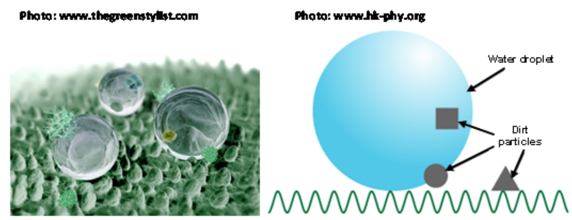
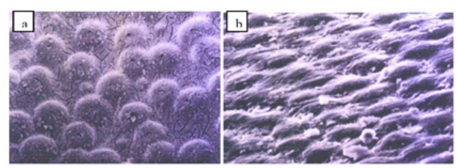
Super Group	Biomimetic Design Principles	Facilitators
Environmental interaction	Use static and/or dynamic structures to replicate (or substitute) the natural environment that optimizes the product/system's performance.	The building mass (concrete floors and walls) serves as an energy source (passive cooling: thermal energy exchange with air drawn from the exterior) in the termite mound inspired Eastgate Building. **Photo: Eastgate, Harare**  **Fresh air is drawn trough the bottom of the building. Heat transfer between the building mass (floors and walls) and air leads to its cooling or heating.**
Function manipulation	Make the same part perform two or more distinct functions.	The sharkskin's dermal denticles (ridged scales) reduce drag by manipulating the water flow over it as well as keep the skin clean due to their structure and shape. **Photo: Sharklet Technologies**  **The nano-scale ridged scales reduce drag by manipulating water flow along the skin.**

Table 7 continued

Super Group	Biomimetic Design Principles	Facilitators
Function manipulation	Prevention over correction: Build preventive functionality into the product/system in place of reactive or corrective functionality to help achieve an overall function.	An important part of the lotus inspired self-cleaning surface's strategy is to prevent the accumulation of dirt rather than react after the dirt has been accumulated.  **The bumped micro-structures on the surface prevent dirt accumulation between the ridges and water droplets carry the dirt particles (on top of the structures) away** The ground beetle's soil engaging components have a surface structure that prevents soil adhesion rather than reacting (to clean) after the soil has already adhered to the surface [55].  **The unsmooth surface morphology on the heads of the dung beetle (left) and desert beetle (right) prevent soil adhesion**
Function manipulation	Use part(s) or feature(s) that is sacrificed after its functionality is achieved.	Plant abscission inspired micro-assembly procedure uses an intermediate part to separate two objects (Microscrew and propylene rod) [18].

5.2 Using the Developed Biomimetic Design Principles

To effectively use the biomimetic design principles, a designer must first comprehensively understand the engineering design problem at hand. Subsequently, the designer must review each biomimetic principle keeping in mind that each principle can potentially offer inspiration for a solution to the problem. The key therefore is to comprehensively review each principle in the context of the problem and avoid missing potential solutions. The procedure outlined below helps guide designers using the biomimetic design principles.

1. Understand the engineering problem at hand.
2. State the problem:
    a. Use general abstract terms and avoid using specific terminology that confines the thought process to conventional existing solution strategies.
    b. The statement must include the desirable as well as undesirable (if any) properties or functions of the required solution.
    c. Such a statement can be made easier to attain by thinking about the required product or design's black box function or functions (if multiple high level functions exist).
3. Review each super group of the biomimetic design principles table to find any specific groups that cannot be used. In other, words if the given design problem constrains the solution path eliminate the super groups that fall outside such constraints (Example: If the structure of the product cannot be changed, eliminate the super group: Structure).
4. Review the rest of the biomimetic design principles and their facilitators individually in the context of the problem statement.
5. While reviewing each principle, attempt to generate conceptual solutions for the problem at hand.

6 CASE STUDIES

This research work has two deliverables: a principle extraction methodology and a set of biomimetic design principles. This section describes in detail two case studies that contribute as a part of the evaluation and validation of the presented research work. The detailed validation of the research work is performed in a later section: Validating the Method: Validation Square.

The first case study assesses the developed principle extraction methodology's effectiveness and reliability in terms of extracting or inferring the requisite principles from a natural system or biomimetic product pair. Two undergraduate students use the methodology separately to analyze two systems: the cricket's flow sensor and the cocklebur inspired Velcro® fastener. Additionally, the author also investigates the two systems using the same methodology. A comparison of the results suggests that the methodology is repeatable and can effectively identify the requisite principles from a given system.

The second case study demonstrates the usefulness of the developed biomimetic design principles themselves. In the study, the principles are used to inspire a conceptual solution to a given design problem. This bio-inspired solution is compared to other solutions that are developed using different idea generation techniques. The analysis of the concept reveals that the biomimetic design principles can inspire novel candidate solutions or products that are innovative and robust. A detailed description and analysis of the case studies is presented in the subsections below.

6.1 Case Study 1: Using the Principle Extraction Methodology

This case study aims to examine and assess the developed methodology's effectiveness in extracting biomimetic design principles from a given natural system or biomimetic product pair. Specifically, the study involves using the developed methodology to extract biomimetic design principles from two systems: the cricket's flow sensor and the cocklebur inspired Velcro® fastener.

The author analyzed these two systems as part of the 23 systems investigated for biomimetic design principles using the developed principle extraction methodology. Therefore, the two systems' underlying biomimetic design principles were already extracted and known.

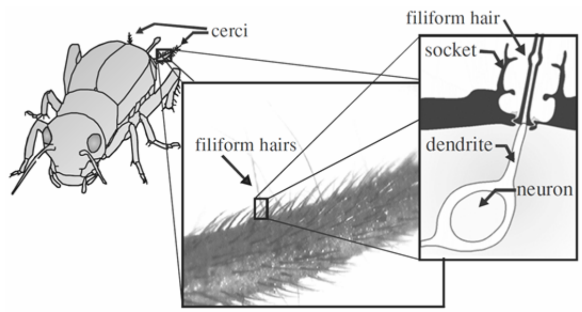
In this case study two undergraduate students, one a mechanical engineering student and the other a biology student, used the methodology to investigate the two systems. The principles extracted by the two students were compared with those extracted by the author from the same systems. This comparison helps examine and assess the developed methodology's repeatability, effectiveness, and validity. The following subsections describe the case study in detail.

6.1.1 System Overview Presented to the Students

Both the students were given a brief description of the two systems to be analyzed and investigated for biomimetic design principles. This helps them understand the system at hand before using the developed methodology to extract the underlying biomimetic design principles. Figure 15 and Figure 16 show the actual cricket's flow sensor and cocklebur inspired Velcro® fastener descriptions provided to the students.

SYSTEM 1: Natural System

Natural System: Cricket's flow sensor
Crickets use mechano-receptive hairs situated on two protruding body appendices called cerci. The flow-sensitive hair and mechanical filtering allow the cricket to perceive signals near the noise limits.

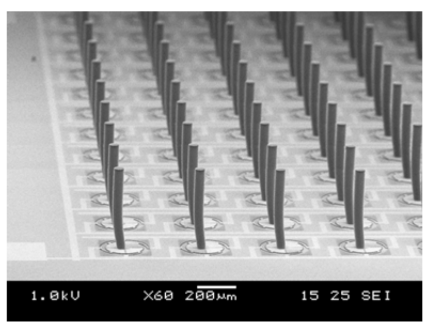


Filiform hairs on the cerci of the cricket senses airflow

Most engineered acoustic sensors use pressure sensing, but the flow sensing ability of the cricket allows it to perceive even at noise limits including thermal noise. This mechanism is adapted to allow the cricket to sense the presence of predators. Predators like wasps are too small to produce significant pressure variations, but there proximity can allow the cricket to sense particle flows resulting from the predator's movement.

Adapted to meet specific requirements, the cricket's hairs are highly sensitive and therefore robust to the designed for conditions. The airflow causes the hair to tilt and in turn apply pressure to neurons in the base socket. This effect is greatly enhanced by the mechanical lever amplification principle. Therefore a cricket can sense movements of small and lightweight predators at close distances.

Proposed bio-inspired engineering application: Flow Sensors
Engineered pressure based sensors cannot perceive sound at the noise limits. Biomimetic designs based on the cricket's mechano-sensing mechanism have been developed. Although, current designs are not as efficient and effective as the biological counterpart, they do show great promise.



Array of spiral-suspended sensory hairs

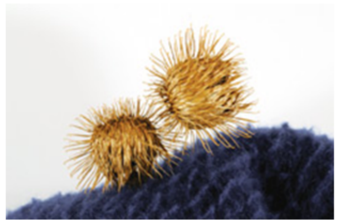
Current acoustic sensing systems perform filtering and amplification using electrical circuits and are therefore have a limited sensing range. Flow sensing allows for a greater sensing range due to the absence of circuit disturbances. Additionally, arranging the flow sensors in a densely packed array allows the system to perceive flow patterns rather than measurements at a single point.

Conventional System: Microphone-Speaker system

Figure 15: Students reviewed this description of a cricket's flow sensor [53]

SYSTEM 2: Biomimetic Product Pair

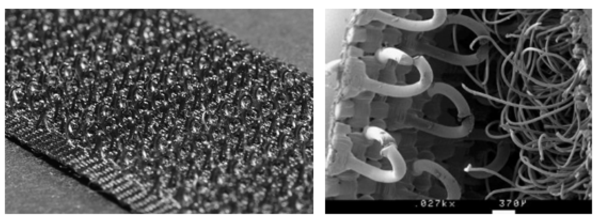
Natural System: Cocklebur plant seed dispersal
The spherical seeds or burs of the cocklebur are covered with small hooks that can attach to animal fur, feathers, and any other fibrous material. Owing to the spherical shape and the densely arrayed hooks on its surface, the burs efficiently disperse the cocklebur seeds using animals and birds for transport.



The cocklebur seed has hooks that attach to animal fur

Therefore, the bur's design is robust to its designed for environment. These characteristics include its lightweight, omni-directional attachment, and hook redundancy.

Bio-inspired engineering product: Velcro® fastener
Inspired by the cocklebur design, the Velcro fastener consists of a strap with densely arrayed hooks and a complementary strap with loose fibers. The hooks attach to the loose fibers allowing the two straps to mate while pulling them apart releases the fiber-hook bond.



Velcro hooks are optimally shaped and sized to attach to mating strap

Unlike, the bur design engineering fastening applications do not necessarily require omni-directionality and therefore specific Velcro straps can be designed for specific applications. This optimized characteristic shape increases the design's robustness to the specific design condition. Additionally, the hook and fiber densities are varied to match the bond strength of the design requirements. The strap with the loose fibers is specifically design to match the hook strap thereby providing an optimized environment for the hooks.

Conventional System: Adhesive tape

Figure 16: Students reviewed this description of the cocklebur inspired Velcro® fastener

6.1.2 Principle Extraction Methodology Provided

In addition to the descriptions of the two systems, the students were also given the principle extraction methodology outline. It is important to note that the principle extraction methodology is not given to the students as is presented in the earlier section: Developed Principle Extraction Methodology. Instead, an edited version without the illustrative examples and the biomimetic principles is provided. This ensures that the students do not know any of the biomimetic design principles before investigating the two systems for the same. In addition, leaving out the example illustrations also helps avoid any bias that can influence the thought process during the two systems' analysis. The actual principle extraction methodology outline presented to the students is shown in subsection III of the appendix.

It is important to note that the two students work at the Product Synthesis Engineering lab as undergraduate research assistants. Therefore, they have a background in using design methodologies like functional modeling and morphological matrices. However, the author was a hand to help with questions regarding the use of any of the design tools used in the principle extraction methodology. In fact, the case study also helped the author edit the developed principle extraction methodology to enhance its instructional presentation and ease of use.

6.1.3 Students' Analysis Results

The students reviewed the descriptions of the two systems and then used the principle extraction methodology outline to analyze them. The students worked through every step of the methodology and documented their work.

They did not have to work through steps 1 and 2 of the principle extraction methodology. This is because the description of the examples presented earlier identified the natural system, the bio-inspired engineering system, and the conventional product. However, the students did have to work through steps 3 through 5 for each system.

Step 6 outlines the method used to abstract the identified characteristics, features, and/or principles into high-level biomimetic design principles. However, this requires reviewing characteristics identified from the analysis of multiple biomimetic product pairs and natural systems. Since the students were analyzing just two systems, finding commonalities to group and abstract the identified characteristics is not possible. Instead, they only identify the underlying characteristics, features, and/or principles that exemplify the biomimetic principles that underline the system's robustness.

The following part of this subsection presents each student's analysis of the cricket's flow sensor and the cocklebur inspired Velcro® fastener. The subsequent subsection reviews and compares each student's results with those of the author's to evaluate and assess the developed methodology's effectiveness.

First student's analysis

The student's analysis of each system included documenting the work done for steps 3 through 5 of the principle extraction methodology. Each system's analysis is presented below.

First student's analysis of system 1: Cricket's flow sensor

As mentioned earlier, the students did not need to work through steps 1 and 2 of the principle extraction methodology. The student used steps 3 through 5 of the principle extraction methodology to investigate the cocklebur inspired Velcro® fastener for characteristics that exemplify its underlying biomimetic principles. The student's documented work is presented below.

- Step 3: Functional modeling

For a natural system, the principle extraction methodology calls for functional models of the natural system and the conventional product. The first student's requisite functional models are presented in Figure 17 and Figure 18 below.

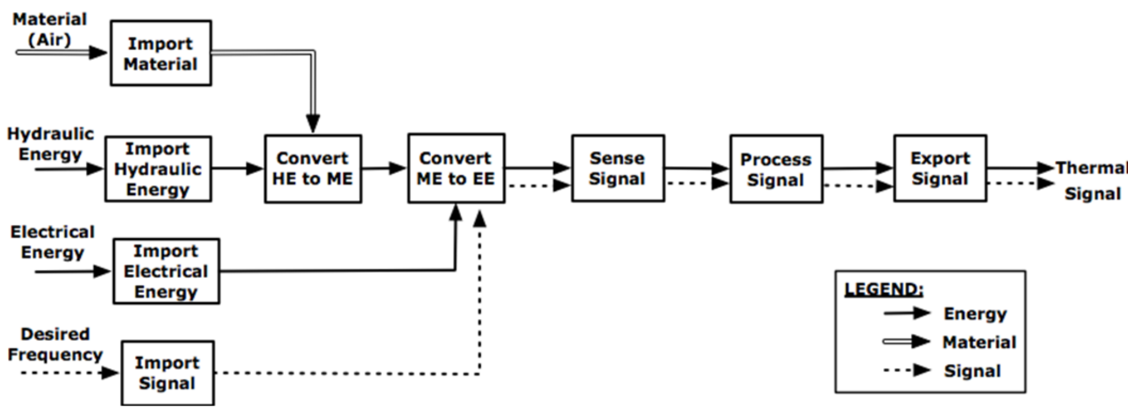


Figure 17: First student's functional model for proposed bio-inspired engineering product: Cricket's flow sensor

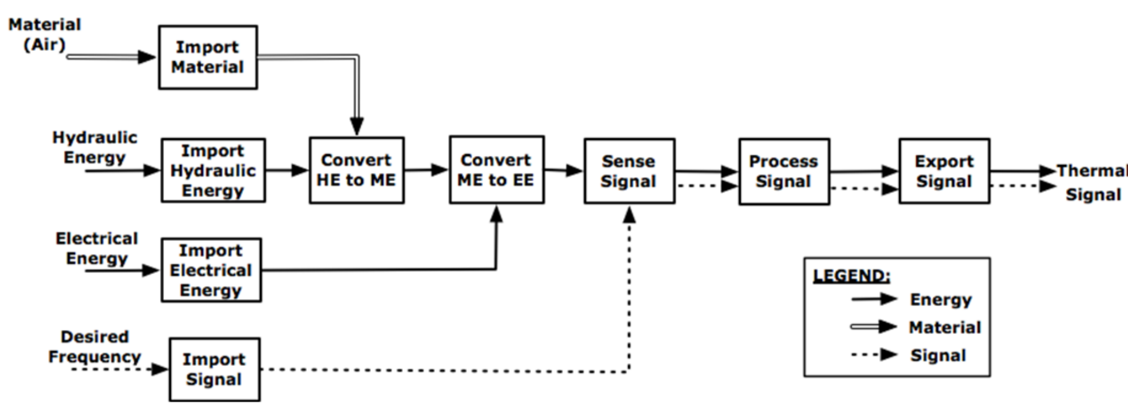


Figure 18: First student's functional model for conventional system: microphone-speaker system

- Step 4: Morphological matrix

The methodology also calls for a comparison between the conventional product, the microphone speaker system and the natural system, the Cricket's flow sensor. This comparison is performed using the morphological matrix as seen in Table 8 below.

Table 8: Morphological matrix developed by the first student helps compare function-flow pairs of the Cricket's flow sensor and the microphone-speaker system

Function-Flow Pairs		**Primary Functionality**	**Components**	
Natural	**Conventional**		**Natural**	**Conventional**
Import material (air/particles)	Import material (air)	Import	Sensory hairs	Diaphragm
Import Hydraulic	Import Hydraulic	Import	Sensory hairs	Arrays, grid
Import Electrical	Import Electrical	Import	Brain	Battery, outlet
Import Signal	Import Signal	Import	Sensory hairs	Electrical wire
Convert HE to ME	Convert HE to ME	Convert	Sensory hairs	Diaphragm
Convert ME to EE	Convert ME to EE	Convert	Brain, neurons	Magnet, wires, coils
Electrical Energy	X	Regulate	No circuit disturbance, filtering	X
Signal	Signal	Sense	Densely packed hairs	Arrays, grid
Signal	Signal	Process	Brain, neurons	Wires, coils
Signal	Signal	Export	Nerves	Wires

In the table above, the red colored font identifies a functional change and the blue colored font identifies a solution approach change as required by the methodology.

- Step 5: Questioning the functional models using the Theory of Highly Optimized Tolerance and the function-behavior-structure representation

In this step, the student reviews the definition of a HOT characteristic, the developed functional models, and the changes identified using the morphological matrix. The system is then investigated by answering the four questions outlined in the methodology. For this example, the student's answers to these questions are presented below.

a. What features/characteristics of the product or system make it robust (as in ensures the successful accomplishment of its overall functions) in terms of functionality within the 'designed-for' environment?
   - *The mechano-receptive hair-like extensions that make them sense low frequency noise*

b. What features/characteristics of the product or system's architecture/structure (or structure) make it robust to its 'designed-for' environment?
   - *The densely packed arrays*

c. What features/characteristics of the product or system's strategy optimize its performance within the 'designed-for' environment?
   - *That there is negative circuit disturbance*

d. How does the product or system ensure effectively achieving its overall objective?

- *Using the negative circuit disturbance, filtering, and amplification*

First student's analysis of system 2: Cocklebur inspired Velcro® fastener

The student used steps 3 through 5 of the principle extraction methodology to investigate the cocklebur inspired Velcro® fastener for characteristics that exemplify its underlying biomimetic principles. The student's documented work is presented below.

- Step 3: Functional Modeling

For a biomimetic product pair, the principle extraction methodology calls for functional models of the bio-inspired engineering product and the conventional product. The student's requisite functional models are presented in Figure 19 and Figure 20 below.

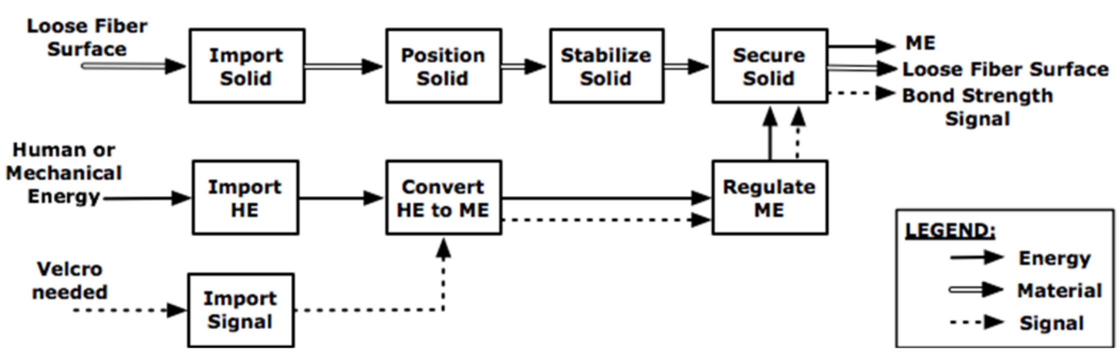


Figure 19: First student's functional model for bio-inspired engineering product: cocklebur inspired Velcro® fastener

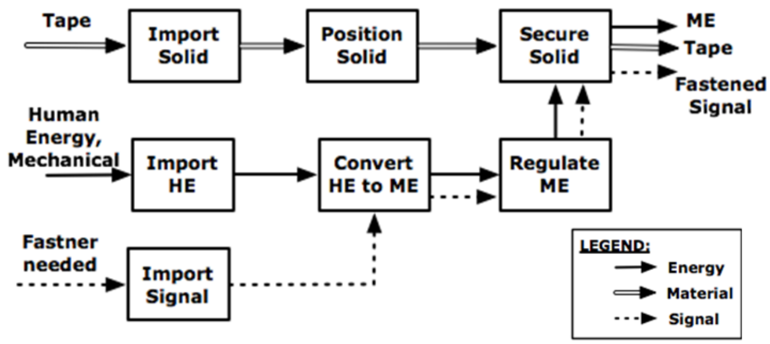


Figure 20: First student's functional model for conventional system: adhesive tape

- Step 4: Morphological Matrix

The methodology also calls for a comparison between the conventional product, an adhesive tape and the bio-inspired engineering product, the Velcro® fastener. This comparison is performed using the morphological matrix as seen in Table 9 below.

Table 9: Morphological matrix developed by the first student helps compare function-flow pairs of the Velcro® fastener and a conventional adhesive tape

Function-Flow Pairs		**Primary Functionality**	**Components**	
Natural	**Conventional**		**Natural**	**Conventional**
Import Solid (loose fiber surface)	Import Solid (tape)	Import	Loose fibers	Tape
Human Energy	Human Energy	Import	Hand/Upper body	Hand/Upper body
Signal	Signal	Import	Brain to hand	Brain to hand
Mechanical Energy	Mechanical Energy	Regulate	Hand/Upper body	Hand/Upper body
Convert HE to ME	Convert HE to ME	Convert	Hand/Upper body	Hand/Upper body
Solid	Solid	Position	Loose fiber to dense array match up	Line up adhesive tape
Solid	X	Stabilize	Attach fibers to array	X
Solid	Solid	Secure	Fibers attach to hook array	Chemical adhesive

In the table above, the red colored font identifies a functional change and the blue colored font identifies a solution approach change as required by the methodology.

- Step 5: Questioning the functional models using the Theory of Highly Optimized Tolerance and the function-behavior-structure representation

In this step, the student reviews the definition of a HOT characteristic, the developed functional models, and the changes identified using the morphological matrix. The system is then investigated by answering the four questions outlined in the methodology. For this example, the student's answers to these questions are presented below.

a. What features/characteristics of the product or system make it robust (as in ensures the successful accomplishment of its overall functions) in terms of functionality within the 'designed-for' environment?
    - *Densely arrayed hooks that attached to the loose fiber strap*

b. What features/characteristics of the product or system's architecture/structure (or structure) make it robust to its 'designed-for' environment?
    - *The hook and fiber densities are designed specifically and can determine the bond strength*

c. What features/characteristics of the product or system's strategy optimize its performance within the 'designed-for' environment?

- *It is improved by not requiring omni-directionality*

d. How does the product or system ensure effectively achieving its overall objective?

- *No answer*

Second student's analysis

The second student's analysis of each system also included documenting the work done for steps 3 through 5 of the principle extraction methodology. Each system's analysis is presented below.

Second student's analysis of system 1: Cricket's flow sensor

The student used steps 3 through 5 of the principle extraction methodology to investigate the cricket's flow sensor for characteristics that exemplify its underlying biomimetic principles. The student's documented work is presented below.

- Step 3: Functional modeling

  For a natural system, the principle extraction methodology calls for functional models of the natural system and the conventional product. The student's requisite functional models are presented in Figure 21 and Figure 22 below.

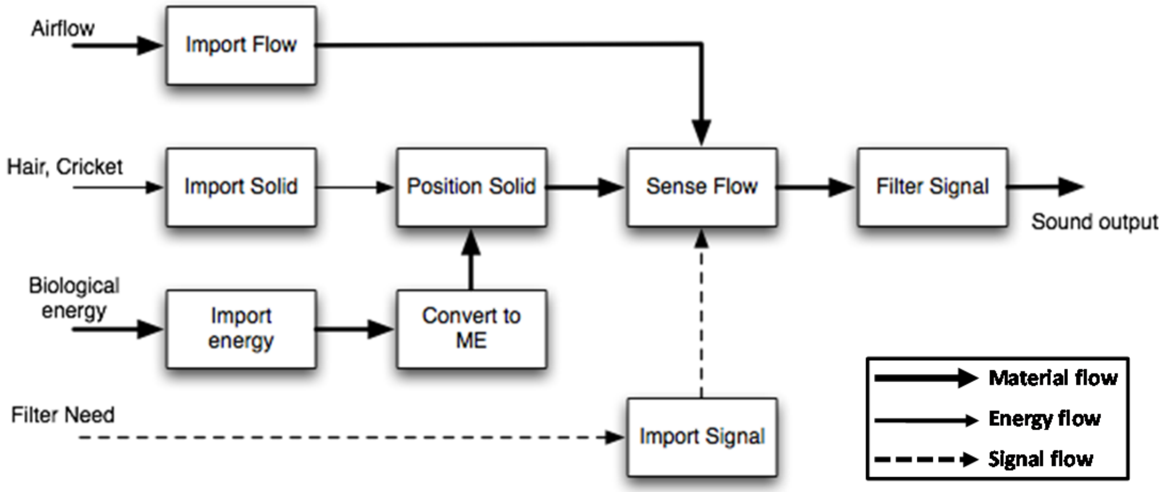


Figure 21: Second student's functional model for proposed bio-inspired engineering product: Cricket's flow sensor

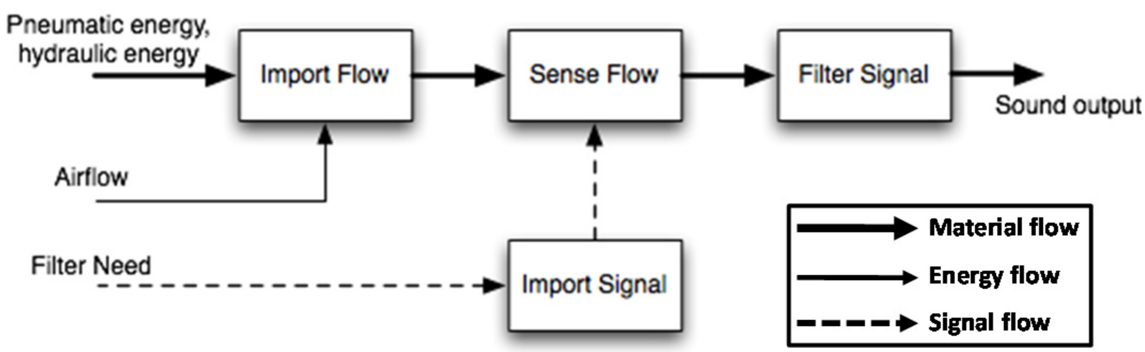


Figure 22: Second student's functional model for conventional system: microphone-speaker system

- Step 4: Morphological matrix

The methodology also calls for a comparison between the conventional product, the microphone-speaker system and the natural system, the Cricket's flow sensor. This comparison is performed using the morphological matrix as seen in Table 10 below.

Table 10: Morphological matrix developed by the second student helps compare function-flow pairs of the Cricket's flow sensor and the microphone-speaker system

Function-Flow Pairs		Primary Functionality	Components	
Natural/Biomimetic Solution	Conventional Engineered Solution		Natural/Biomimetic Solution	Conventional Engineered Solution
Import material (airflow)	Import material (airflow)	Import	Cricket hair	Microphone
Import solid (hair, cricket)	X	Import	Cricket	X
Import energy (biological)	X	Import	Cricket	X
Import signal	Import signal	Import	Cricket sensor	Sensor
Position solid (hair)	X	Position	Cricket hair	X
Convert to mechanical energy	X	Convert	Cricket arm	X
Sense airflow	Sense airflow	Sense	Densely packed array of hairs	Diaphragm
Filter signal	Filter signal	Filter	Cricket neuron's base structure (muscle)	Signal processor

In the table above, the red colored font identifies a functional change and the blue colored font identifies a solution approach change as required by the methodology.

- Step 5: Questioning the functional models using the Theory of Highly Optimized Tolerance and the function-behavior-structure representation

In this step, the student reviews the definition of a HOT characteristic, the developed functional models, and the changes identified using the morphological matrix. The system is then investigated by answering the four questions outlined in the methodology. For this example, the student's answers to these questions are presented below.

a. What features/characteristics of the product or system make it robust (as in ensures the successful accomplishment of its overall functions) in terms of functionality within the 'designed-for' environment?
   - *Flow sensing allows for a greater sensing range due to the absence of circuit disturbances*

b. What features/characteristics of the product or system's architecture/structure (or structure) make it robust to its 'designed-for' environment?
   - *Array of spiral-suspended sensory hairs*

c. What features/characteristics of the product or system's strategy optimize its performance within the 'designed-for' environment?
   - *Arrangement of the flow sensors*

d. How does the product or system ensure effectively achieving its overall objective?
   - *No answer*

Second student's analysis of system 2: Cocklebur inspired Velcro® fastener

The student used steps 3 through 5 of the principle extraction methodology to investigate the cocklebur inspired Velcro® fastener for characteristics that exemplify its underlying biomimetic principles. The student's documented work is presented below.

- Step 3: Functional Modeling

For a biomimetic product pair, the principle extraction methodology calls for functional models of the bio-inspired engineering product and the conventional product. The student's requisite functional models are presented in Figure 23 and Figure 24 below.

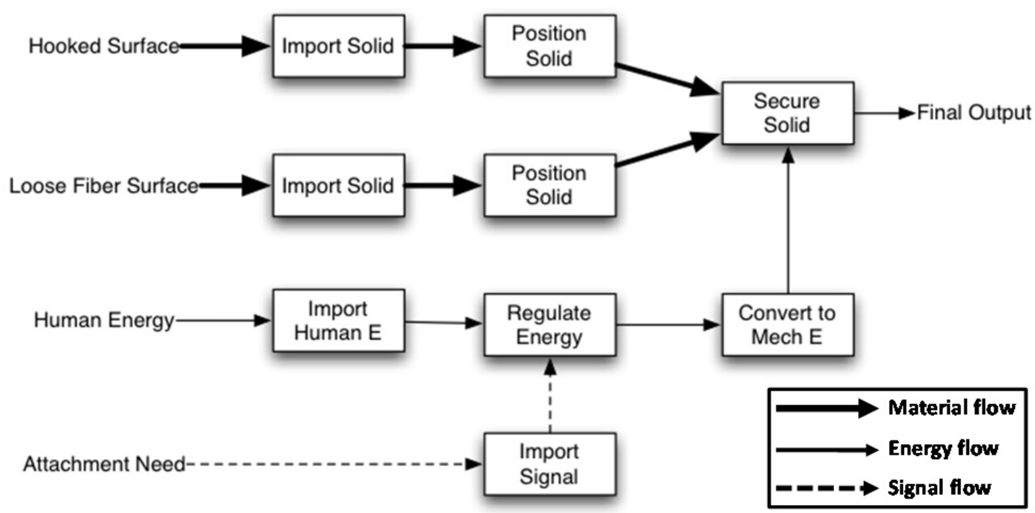


Figure 23: Second student's functional model for bio-inspired engineering product: cocklebur inspired Velcro® fastener

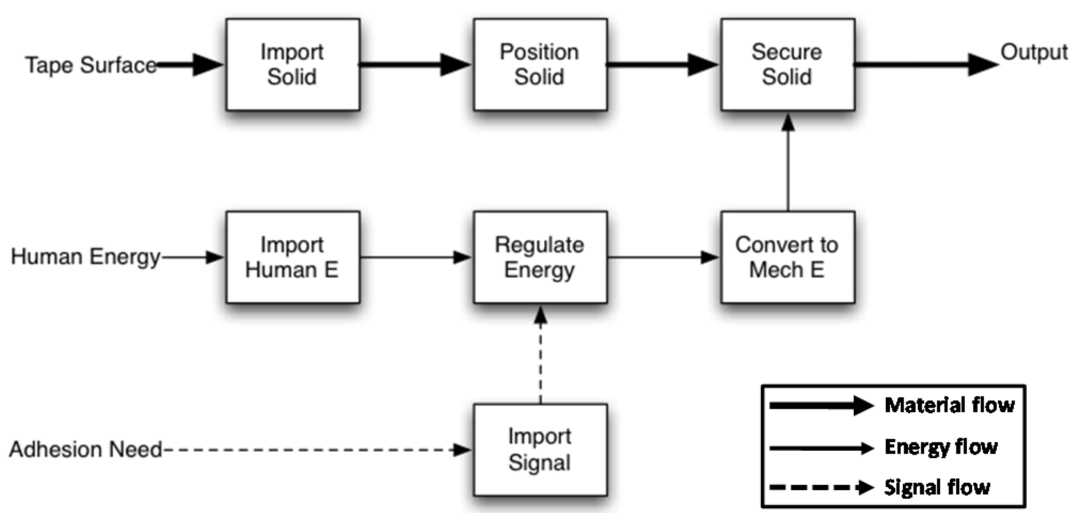


Figure 24: Second student's functional model for conventional system: adhesive tape

- Step 4: Morphological Matrix

The methodology also calls for a comparison between the conventional product, an adhesive tape and the bio-inspired engineering product, the Velcro® fastener. This comparison is performed using the morphological matrix as seen in Table 11 below.

Table 11: Morphological matrix helps compare function-flow pairs of the Velcro® fastener and a conventional adhesive tape

Function-Flow Pairs		**Primary Functionality**	**Components**	
Natural/Biomimetic Solution	**Conventional Engineered Solution**		**Natural/Biomimetic Solution**	**Conventional Engineered Solution**
Import solid (hooked surface)	Import solid (external surface)	Import	Hand	Hand
Import solid (loose fiber surface)	X	Import	Hand	X
Import human energy	Import human energy	Import	Hand	Hand
Import signal	Import signal	Import	Brain	Brain
Position solid (loose fibers)	Position solid (external surface)	Position	Hand	Hand
Position solid (hooked surface)	X	Position	Hand	X
Regulate energy	Regulate energy	Regulate	Hand	Hand
Secure solid	Secure solid	Secure	Velcro fibers	Chemical coating
Convert to mechanical energy	Convert to mechanical energy	Convert	Hand	Hand

In the table above, the red colored font identifies a functional change and the blue colored font identifies a solution approach change as required by the methodology.

- Step 5: Questioning the functional models using the Theory of Highly Optimized Tolerance and the function-behavior-structure representation

In this step, the student reviews the definition of a HOT characteristic, the developed functional models, and the changes identified using the morphological matrix. The system is then investigated by answering the four questions outlined in the methodology. For this example, the student's answers to these questions are presented below.

a. What features/characteristics of the product or system make it robust (as in ensures the successful accomplishment of its overall functions) in terms of functionality within the 'designed-for' environment?
   - *The hooks attach to the loose fibers allowing the two straps to mate while pulling them apart releases the fiber-hook bond*

b. What features/characteristics of the product or system's architecture/structure (or structure) make it robust to its 'designed-for' environment?
   - *Shape of straps*

c. What features/characteristics of the product or system's strategy optimize its performance within the 'designed-for' environment?
   - *Optimized characteristic shape. Strap with loose fibers specifically designed to match hook strap*

d. How does the product or system ensure effectively achieving its overall objective?
    - *No answer*

6.1.4 Reviewing and Comparing the Results

Reviewing and comparing the characteristics, features, and/or principles identified by the author and the two students can help assess the developed methodology's effectiveness and repeatability. The characteristics, features, and/or principles are simply the answers to the four questions asked of the system as part of the principle extraction methodology. They exemplify the biomimetic design principles that underline the system's robustness within its designed-for environment.

It is important to recall, that these answers are not stated as design principles. Once these characteristics are obtained for all the systems under analysis, they are reviewed and grouped to develop abstract high-level biomimetic design principles. However, this subsection is restricted to the analysis of just two systems: the cricket's flow sensor and the cocklebur inspired Velcro® fastener. Therefore, the comparison between the author and the students' analysis of the given systems is performed at the level of the characteristics identified from the systems and not at the level of the design principles. For each system, the review and comparison of the identified characteristics is presented below.

Review and comparison of cricket's flow sensor analysis

The answers or characteristics identified from the author's review of the cricket's flow sensor are listed below. Also listed are the answers and characteristics identified by the students as part of the case study.

- Cricket flow sensor's characteristics identified by author:
    - The cricket inspired flow sensor's array of hair-like fibrous structures ensures sensing redundancy
    - Shape and size of the cricket inspired flow sensor's mechano-receptive hair allows for higher sensitivities

- Cricket flow sensor's characteristics identified by student 1:
    - The mechano-receptive hair-like extensions that make them sense low frequency noise
    - The densely packed arrays
    - That there is negative circuit disturbance
    - Using the negative circuit disturbance, filtering, and amplification

- Cricket flow sensor's characteristics identified by student 2:
    - Array of spiral-suspended sensory hairs
    - Arrangement of the flow sensors
    - Flow sensing allows for a greater sensing range due to the absence of circuit disturbances

The lists show that both students using the principle extraction methodology extracted or inferred the two characteristics identified by the author for the cricket's flow sensor. This correlation helps demonstrate the proposed methodology's effectiveness and repeatability with respect to extracting or identifying biomimetic design principles from natural systems.

The first characteristic refers to the sensor's use of an arrayed arrangement of multiple structures. Student 1 identifies this underlying characteristic using the terms: "densely packed array". Similarly, student 2 identified this underlying characteristic using the terms: "array of spiral-suspended sensory hairs" and "arrangement of the flow sensors".

The second characteristic highlights the sensor's use of specifically shaped and sized mechano-receptive hair-like structures that allow for higher sensitivities. Student 1 identifies this underlying characteristic in the words: "mechano-receptive hair-like extensions that make them sense low frequency noise". Similarly, student 2 identifies this underlying characteristic in the words: "spiral-suspended sensory hairs".

Interestingly, both students also identified additional characteristics that are not listed by the author. These additional characteristics reflect the properties of the bio-inspired flow sensor and not the natural system. This implies that the students answered a subset of the four questions in the context of the bio-inspired flow sensor.

However, when analyzing a natural system and a proposed bio-inspired system, the principle extraction methodology requires answering all the questions in the context of the natural system. A proposed bio-inspired system in the design phase is not completely functional and is not considered to be a reliable source for design principles.

Following this case study, the methodology is modified to include an explicit statement that informs the designer to focus on the natural system (in this case the cricket's flow sensor) when answering these questions.

Review and comparison of cricket's flow sensor analysis

The answers or characteristics identified from the author's review of the cocklebur inspired Velcro® fastener are listed below. Also listed are the answers and characteristics identified by the students as part of the case study.

- Cocklebur inspired Velcro® fastener's characteristics identified by author:
  - Velcro's array of discrete hooks ensures mating redundancy to a fibrous strap.
  - The shape and size of the hooks are optimized to attach to the fibrous strap.
  - Using a dedicated fibrous mating strap optimized to attach to the designed hooks ensures the hooks' ability to achieve their function.
  - The cocklebur plant's seeds leverage the surrounding environment (animals with fur, birds with feathers) for dispersal

- Cocklebur inspired Velcro® fastener's characteristics identified by student 1:
  - Densely arrayed hooks that attached to the loose fiber strap
  - The hook and fiber densities are designed specifically and can determine the bond strength
  - It is improved by not requiring omni-directionality

- Cocklebur inspired Velcro® fastener's characteristics identified by student 2:
    - The hooks attach to the loose fibers allowing the two straps to mate while pulling them apart releases the fiber-hook bond
    - Shape of straps
    - Optimized characteristic shape. Strap with loose fibers specifically designed to match hook strap

The lists show that both students using the principle extraction methodology extracted or inferred the three characteristics identified by the author for the cocklebur inspired Velcro® fastener. As with the earlier example, this correlation helps demonstrate the proposed methodology's effectiveness and repeatability in terms of extracting biomimetic design principles from biomimetic product pairs.

The first characteristic reflects the Velcro® fastener's use of multiple hooks in an arrayed arrangement. Student 1 identifies this underlying characteristic in the words: "densely arrayed hooks that attached to the loose fiber strap". Similarly, student 2 identifies this underlying characteristic in the words: "hooks attach to the loose fibers".

The second characteristic highlights the specific shape and size of the Velcro® fastener's hooks. Student 1 identifies this underlying characteristic using the phrase: "hook densities are designed specifically". Similarly, student 2 identifies this underlying characteristic using the phrase: "shape of straps".

Lastly, the third characteristic refers to the use of a dedicated mating strap that ensures effective adhesion. Student 1 captures this underlying characteristic in the words: "fiber densities are designed specifically" and "it is improved by not requiring omni-directionality". Similarly, student 2 captures this underlying characteristic in the words: "strap with loose fibers specifically designed to match hook strap".

It is also important to note that the fourth characteristic identified by the author is not identified by either of the students. The author identified this specific characteristic from the analysis of the cocklebur plant's seed. Therefore, the fourth characteristic reflects the properties of the natural system (that is the cocklebur plant's seed). However, when analyzing a biomimetic product pair the principle extraction methodology requires answering the four questions in the context of the bio-inspired product. This is the reason the neither of the students identified this specific characteristic. On the other hand, the author identified the characteristic in question during work performed for a previous paper that formed the basis for this work [7].

6.1.5 Case Study Overview

As mentioned earlier, this case study is used to assess the proposed methodology's effectiveness and repeatability in extracting design principles from natural systems and biomimetic product pairs. The results of using the proposed methodology to investigate a natural system and a biomimetic product pair are summarized below.

- For the natural system and the biomimetic product pair, both the students were able to identify the characteristics identified by the author.
- For the natural system both students identified an additional characteristic. This is attributed to the students' consideration of the proposed bio-inspired system in the analysis. The principle extraction methodology is appropriately modified.

- For the biomimetic product pair the author identified an additional characteristic. This characteristic reflects properties of the natural system, the cocklebur plant's seed. The methodology does not require asking questions of the natural system when analyzing a biomimetic product pair. Therefore, the students are not expected to identify this specific characteristic.

The results show that when used as outlined, the proposed principle extraction methodology can help infer the similar system characteristics repeatedly. Similarly, the results also show that different users can use the principle extraction methodology to identify similar system characteristics from a given natural system or biomimetic product pair. However, the results also suggest that a user's interpretation of the methodology can affect the characteristics inferred from a given system. The author used the students' feedback to modify and improve the presentation of the proposed principle extraction methodology.

The correlation between the students' results and the author's results helps demonstrate the proposed principle extraction methodology's effectiveness and repeatability with regards to inferring system characteristics that exemplify biomimetic design principles.

6.2 Case Study 2: Applying the Biomimetic Design Principles

This case study aims to highlight the usefulness of the biomimetic design principles developed in this work. The principles are used to inspire a candidate solution for an engineering design problem. As part of the study, the inspired solution is evaluated against the design requirements and also compared to other solutions developed using different idea generation tools.

The author was exposed to this design problem as part of the graduate design class at Texas A&M University. This class aims to teach students the various parts of the design process and the tools available to aid the process. Different groups of students work on different design problems throughout the duration of the class. It culminates in a final report that includes a description of the problem, the methods or tools used to generate conceptual solutions, and the selection of a final solution or design. The author was part of a group of three students assigned the following problem [56].

6.2.1 Problem Statement

There is a need to design a retractable back-up seal that deploys with a bridge plug's sealing element and prevents the extrusion of the sealing element under high differential pressures.

6.2.2 Goals

The goals for the project were highlighted with the problem statement and are listed below.

1. Must activate (or expand) and de-activate (or retract) using available compression and expansion loading mechanisms.

2. The back-up seal must provide the primary sealing element (rubber element) with structural support against the fluid or gas pressure forces.
3. The back-up seal must be retrievable and therefore must retract to its original size when wellbore is to be opened.

6.2.3 Problem Background

Retrievable bridge plug assemblies are commonly used down-hole tool in the oil and gas industry. The major function of a bridge plug is to seal the wellbore at a desired location. It seals the gap between the production tubing and the outer wellbore casing as seen in Figure 25 below.

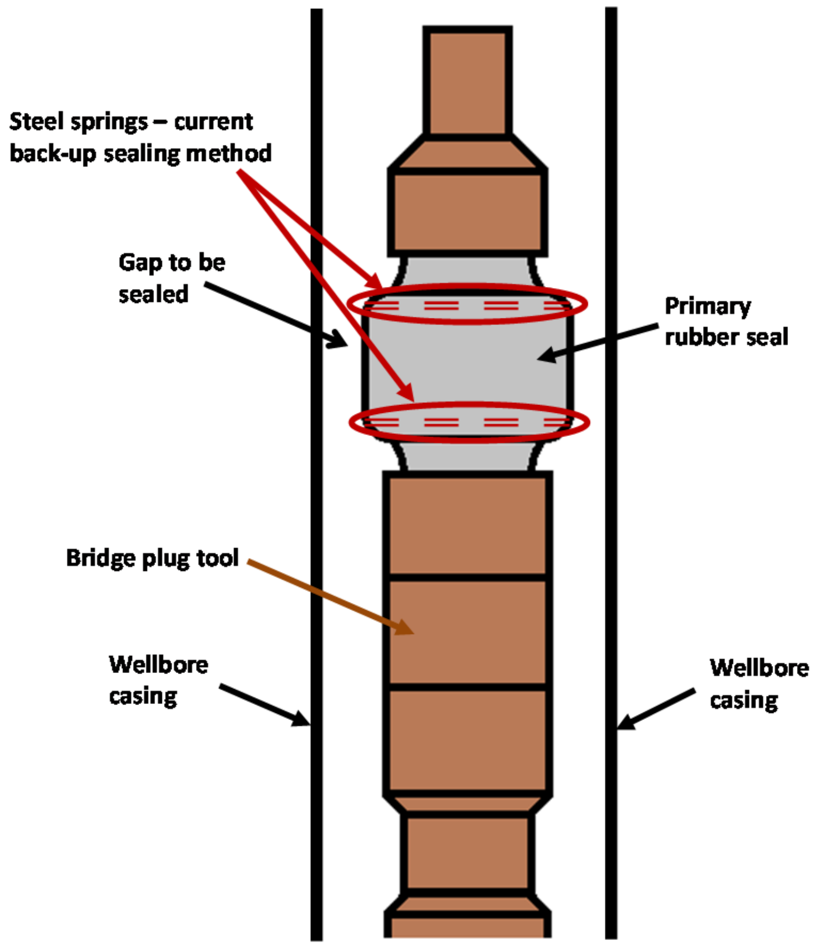


Figure 25: The primary rubber seal and the metallic springs molded into its ends forms the current sealing system for the bridge plug

The sealing system used in this bridge plug consists of a primary seal and the secondary or back-up seal. An expandable and retractable high strength rubber element provides the primary sealing function, while a stiff metallic spring on either side of this rubber element provides the back-up sealing function.

1. Primary Seal:

   As mentioned earlier, the rubber seal above fulfills the sealing function by expanding outwards in the radial direction. Compressing the rubber seal in the vertical direction triggers this outward expansion. If the wellbore needs to be reopened, this compressive force is removed and the rubber returns to its original shape releasing the seal.

2. Back-up seal:

   Two stiff metallic springs make up the back-up seal. A single spring is molded into each end of the rubber seal. Owing to their higher stiffness, the springs increase the stability, strength, and structural integrity of the seal.

On the whole, the seal must have the necessary structural integrity to withstand high fluid pressures inside the wellbore while also preventing any leakage. While this design has been used successfully thus far, increasingly stringent regulations and deeper wells with higher differential pressures have led to the requirement of a more robust solution. This current design needs to be improved and any new design must address the two major drawbacks: low structural integrity and tendency to leak.

Structural integrity

The rubber and metallic spring composite seal's elasticity not only makes the seal reusable, but also allows it to adapt and conform its shape to fit the wellbore casing and thereby provide a tight fit. However, the elasticity also limits the seal's structural integrity. This leads to failures especially when sealing high-pressure wellbores.

Leakage

While the higher stiffness of the springs help in increasing the seal's resistance to fluid pressure during deployment, they also cause problems. This is because their higher stiffness in comparison to that of the rubber leads to a non-uniform expansion of the composite seal under compression loading. As the spring stretches while the seal expands, it pulls on the rubber around it. Additionally, as the springs expand gaps between the steel windings leave the rubber seal exposed to the pressurized fluid. These factors result in tears at the rubber-spring interface leading to leaks.

These disadvantages point to the need for a new back-up sealing mechanism. This new design must be better than the current solution (metallic springs) and must meet four key needs.

1. The back-up seal must activate under compression and deactivate under tension as with the existing design.
2. The back-up seal must be retractable to ensure easy removal if wellbore needs to be reopened.
3. The new back-up seal must provide improved structural support to the rubber seal without compromising its sealing integrity.
4. When deployed together the new back-up seal and rubber seal must not leak.

The problem stated above was assigned to the author's team as the graduate design class project. Before proceeding to the idea or concept generation stage of the project, the team studied the problem, its background, and the company's needs to develop a need statement, a black box diagram, and a set of customer needs for the required design.

6.2.4 Concept: Expanding Ring Concept

Idea generation is an integral part of the design process as a design's success greatly depends on the strength of the concepts themselves. As part of the design class, the team was introduced to many different tools and methods that help with generating ideas for concepts. Therefore, the team used various idea generation techniques to develop a number of concepts for the back-up seal design problem.

Inspiration for the double expanding ring concept came from two sources: the TIPS/TRIZ principles for innovative engineering design and the biomimetic design principles (developed as part of this research). The following subsections describe all the salient features of the double expanding ring concept and the inspiring principle (from TRIZ or the set of biomimetic principles) for each of those features. Thus, the design's achieved usefulness with regards to the initial purpose is tied to the application of certain design principles. The following subsection details the inspirations drawn from both the TRIZ principles as well as the biomimetic design principles.

6.2.5 Inspiration From TRIZ and Biomimetic Design Principles

To effectively use TRIZ as an idea generation tool, the team followed four basic steps: state the problem in a general yet precise manner, analyze and understand the problem to uncover main conflicts or contradictions, identify TRIZ design principles that correspond to the conflicts, and finally use the principles to inspire concepts.

The first step involves stating the problem correctly and is essential when using the TRIZ contradiction matrix as a concept generation tool. It is important to avoid specific terminology as this often confines the designer's thought process to conventional or existing solutions for the problem. The statement should also reflect the desirable and/or undesirable properties or functions of the required solution. Based on these guidelines, the team restated the back-up seal problem for the TRIZ method as follows: Design a back-up seal that expands and retracts with the rubber seal while also providing structural support to resist high pressures during deployment.

These needs imply that the back-up seal must be elastic yet strong. The TRIZ contradiction matrix is essentially a look-up matrix. Each row and column is assigned to one of 39 engineering parameters or factors. A designer looks up the principles that solve contradicting parameters using the row and column they represent in the matrix. In general, the row must represent the parameter that is to be improved, while the column is the parameter that deteriorates. The identified cell would contain a list of appropriate design principles that solve the specific conflict. Altshuller and his colleagues reviewed over 3 million patents and identified 40 principles that solve a set of common engineering conflicts [9]. The matrix relates each conflict based on the specific row and column to the relevant principles that potentially help solve it.

Therefore, it is essential to state the specific engineering conflict of the problem in terms of the 39 TRIZ parameters. For the back-up seal we have identified elasticity versus strength as the conflict. This is because flexibility generally implies a reduction is strength. Of the 39 parameters, this conflict is best represented by flexibility (parameter 35) versus strength (parameter 14) [39]. From the problem background, it is evident that the seal's strength needs to be improved while its flexibility must also be maintained.

In the third step, the team identifies the principles that solve the strength versus flexibility contradiction. Looking up row 14 and column 35 of the contradiction matrix leads to the identification of the following principles.

Principle 15: Principle of dynamism

Make the object or environment able to change to become optimal at any stage of work. Make the object consist of parts that move relative to each other. If the object is fixed, make it movable.

Principle 3: Principle of local quality

Change the object's or environment's structure from homogeneous to non-homogeneous. Let different parts of the object carry different functions.

Principle 32: Principle of using color

Change the color or translucency of an object or its surroundings. Use colored additives to observe certain objects or processes. If such additives are already used, employ luminescence traces.

The final step is to use these identified principles to inspire conceptual solutions for the design problem. Here, the author used the TRIZ principles stated above and the biomimetic design principles as a source of inspiration.

This is an inherently subjective process and the resulting concepts developed depend on the designer's background. However, one can identify the inspiring principle with the inspired feature of the concept. Identifying these links can help understand how a specific principle inspired a specific solution strategy and thereby show its usefulness with regards to addressing the design problem's needs. Each principle and its inspiring feature or strategy for the double expanding ring concept is explained in detail below.

Inspiration from TRIZ Principle 15

This principle's recommendation to make an object dynamic and its motion relative to other parts inspired the idea of replacing the springs molded into the rubber with 'expanding rings' that line the outside of the rubber seal. This allows for a relative motion between the primary rubber seal and the rings during expansion or retraction. The design for the proposed 'expanding ring' is not yet identified at this point. Just the concept of placement and the idea of relative expansion are inspired by this principle as seen in Figure 26 below.

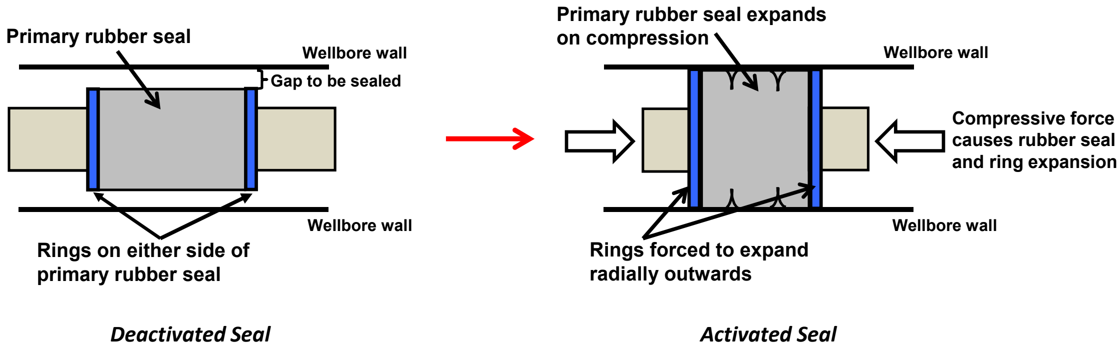


Figure 26: The envisioned expanding rings would sandwich the primary rubber seal giving it structural stability and protection against the external pressurized fluid

Inspiration from biomimetic design principle – Structures super group

The biomimetic principle for composite structures states the following: Make single part from two or more parts with distinct material properties and functionalities.

This principle inspired the design or structure of the 'expanding ring' concept that employs different parts with distinct material properties, structural properties, and functionalities to meet the different requirements of the expanding ring concept. The expanding ring consists of three distinct parts: two hollow c-shaped steel rings, two steel connectors, and two metallic springs. The initial or preliminary sketch for the proposed design is presented in Figure 27 below.

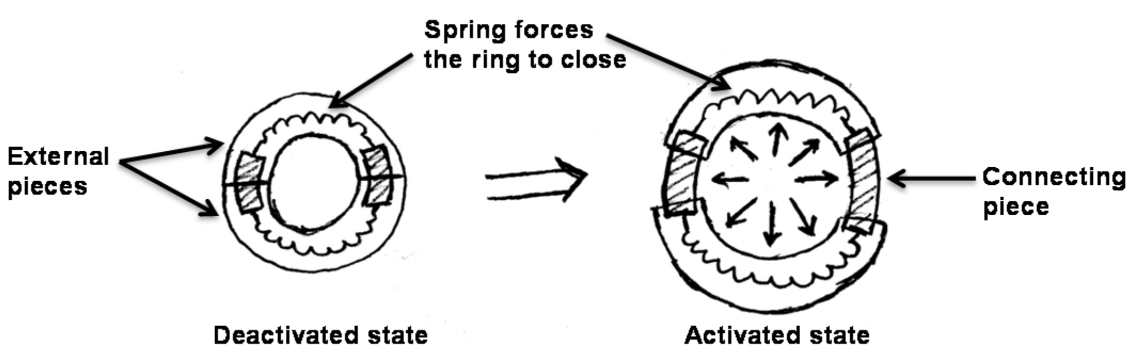


Figure 27: Sketch for proposed composite ring design

The expanding ring not only expands and retracts but also is very strong and durable in the face of external pressure forces. The hollow c-shaped rings and the small steel connectors can easily withstand high external pressures without deforming. This protects the primary rubber seal and internal springs from the fluid pressure forces. On the other hand, the internal springs form the core of the design's flexibility in terms of expansion and retraction. Additionally, the springs do not provide the sealing requirement and therefore their expansion does not expose the primary rubber seal to the pressurized fluid.

Inspiration from TRIZ Principle 3 and Biomimetic Design Principle – Environmental interaction Super Group

Principle 3 from the TRIZ contradiction matrix suggests changing the object's structure from homogeneous to non-homogenous. The biomimetic design principle for environmental interaction is stated as follows: Use materials and/or energy from the environment to help the product/system accomplish its function. For the proposed design, the expanding ring (representing the product or system) operates within the wellbore casing (representing the environment).

These principles inspired the author to adapt the ring's external surface to use or take advantage of its environment, the wellbore casing. The adaptation includes replacing the smooth (or homogeneous) surface with one that is toothed (or non-homogeneous) as seen in the Figure 28 below.

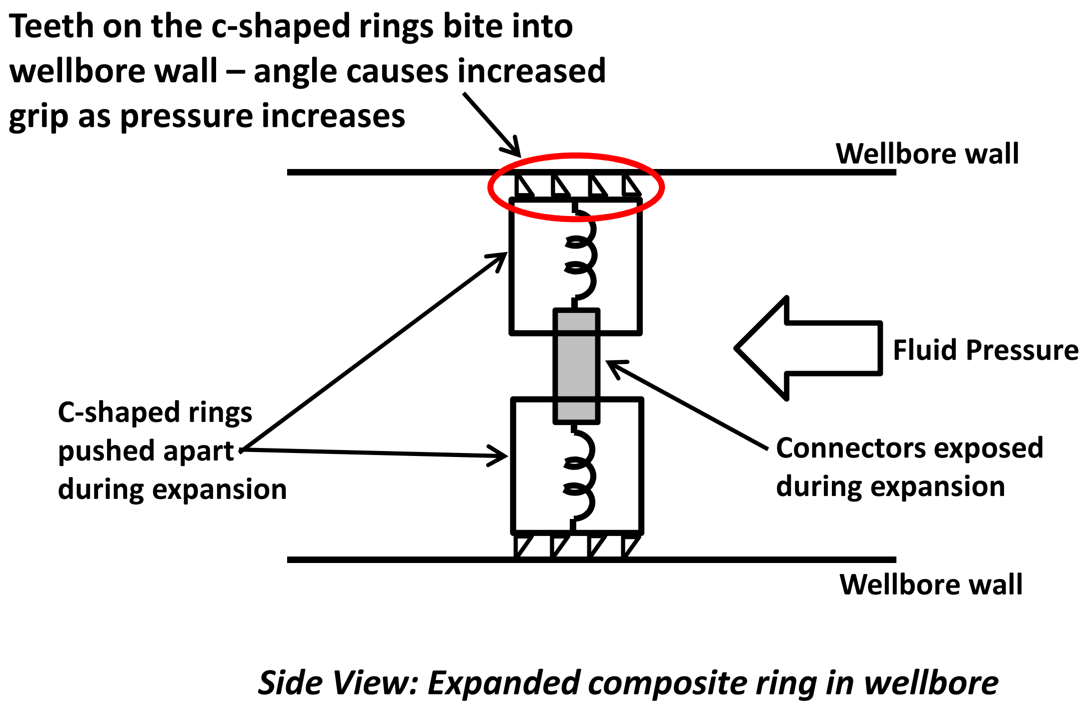


Figure 28: Teeth along the external surface of the c-shaped rings bite into the wellbore casing and hold the composite ring resist the external fluid pressures and stay in place

As the ring expands radially outwards, the teeth bite into the wellbore casing to hold the ring in place. As a result, the rings leverage the strength of the rigid casing to the resist pressure forces that could cause the ring to slip along the wellbore casing.

Inspiration from biomimetic design principle – Structures super group

Having developed the concept using the inspirations detailed above, the team realized that while the expanding ring effectively and optimally met the combined need for flexibility and strength, it failed the need to provide a complete seal. This is because when the ring expands a small gap is exposed around the steel connectors between the two c-shaped rings as seen in Figure 29 below.

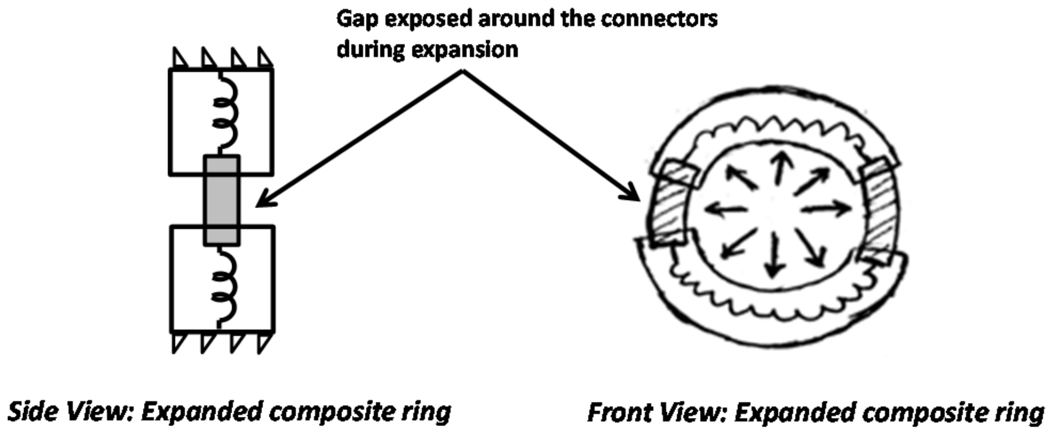


Figure 29: On expansion the c-shaped rings expose a gap around the smaller connectors

The biomimetic design principles were reviewed to find a solution to the expanding ring's failure to effectively seal. The solution was found through inspiration provided by the biomimetic design principle: Substitute discrete self-similar features in place of a single feature used to achieve a critical function.

Two identical expanding rings replaced the single expanding ring to be placed on either side of the primary rubber seal. The two rings sit side-by-side with one rotated 90 degrees relative to the other. This essentially closes the gap exposed by the c-shaped rings when only one ring is used. Figure 30 below illustrates the new design.

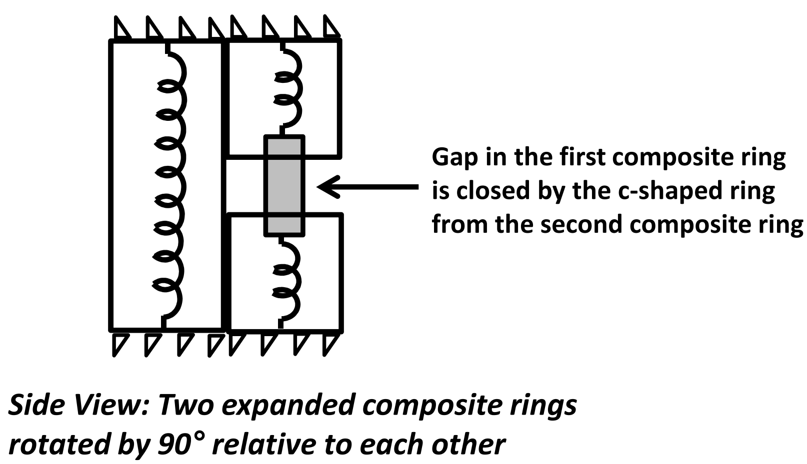


Figure 30: Two rings in parallel close the exposed gap exposed during expansion

The proposed bio-inspired and TRIZ inspired expanding ring design is simple yet effective with respect to the back-up seal's design requirements. In the following subsection, the concept is evaluated against the original design requirements as well as the other concepts or solutions developed by the team.

6.2.6 Concept Evaluation

The previous subsection described how the expanding ring design draws inspiration from various TRIZ and biomimetic design principles. Here, the expanding ring design is evaluated against the four requirements or needs to be met by the back-up seal.

1. *The back-up seal must activate under compression and deactivate under tension as with the existing design.*

   Like the original back-up seal design, the expanding ring uses springs to allow for radial expansion and retraction under compression and tension along the perpendicular axis.

2. *The back-up seal must be retractable to ensure easy removal if wellbore needs to be reopened.*

   The internal springs force the composite expandable ring to close when the compressive force (along the perpendicular axis) on the ring is relaxed.

3. *The new back-up seal must provide improved structural support to the rubber seal without compromising its sealing integrity.*

   Two expandable rings on either side of the primary rubber seal provide the primary rubber seal with the required structural stability. The strong c-shaped rings protect the internal springs as well as the rubber from the well's pressurized fluid.

4. *When deployed together the new back-up seal and rubber seal must not leak.*

   For the original design with springs molded into the rubber seal, leakage was caused due to tears in the rubber at the spring-rubber interface. This is because the steel springs and the rubber seal have different expansion characteristics. Additionally, as the springs expand gaps between the steel windings leave the rubber exposed to the pressurized fluid.

   In contrast, the springs in the expandable ring concept are housed inside solid c-shaped rings. Since these springs do not contribute to the structural strength, they are not very stiff and therefore easy to stretch. As a result, the expandable ring expands easily with the rubber seal and the disparity between the expansion characteristics is reduced. This prevents the primary rubber seal from any damage and therefore ensures a tight seal on deployment.

A question that comes to mind after evaluating the concept with respect to the problem's needs is the following: How does the expanding ring concept fair against the other concepts developed by the team? The simple answer to this question is that the expanding ring concept was chosen as the best solution out of all the concepts developed by the team. Of all the concepts developed by the team, only three were chosen (based on preliminary analysis) for extensive testing [56]. The three chosen concepts were the double expandable ring concept, the internal expansion concept, and the conical ring back-up concept.

As part of the class project, the team then comprehensively compared the three concepts to identify the best solution for the design problem. The down-selection procedure used data from concept modeling and simulation in Solid Works®, finite element analysis, and physical prototyping (where possible). A Pugh chart helped compare the concepts to a common datum, which in this case was the current solution. It is important to note that the Pugh chart in only used to compare four known design concepts. Therefore, it is not to claim that the chosen design is the best possible solution to the design problem. While a detailed overview of the other two concepts is beyond this report, an overview of the expanding ring concept's analysis is presented in Figure 31 below.

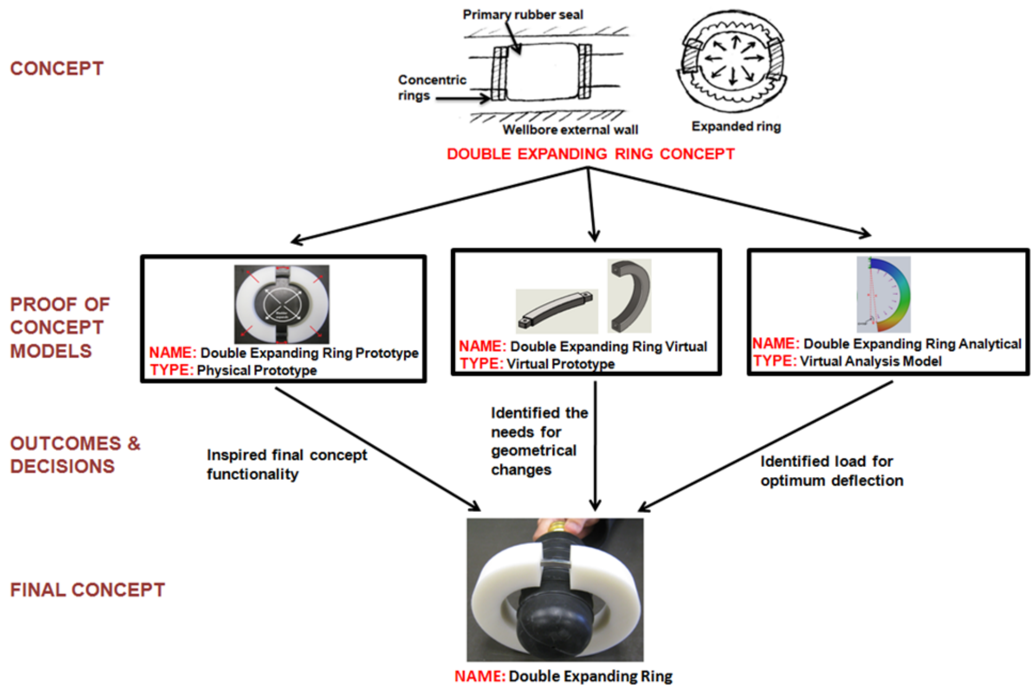


Figure 31: Overview of expanding ring concept analysis and testing

The overall functionality and acceptability of the expanding ring concept was evaluated using a physical prototype, an analytical model, and a finite element analysis of the developed model. The prototype serves to analyze the design's feasibility in terms of effectively achieving the functions of expansion and retraction. This proof-of-concept prototype is illustrated in Figure 32 below.

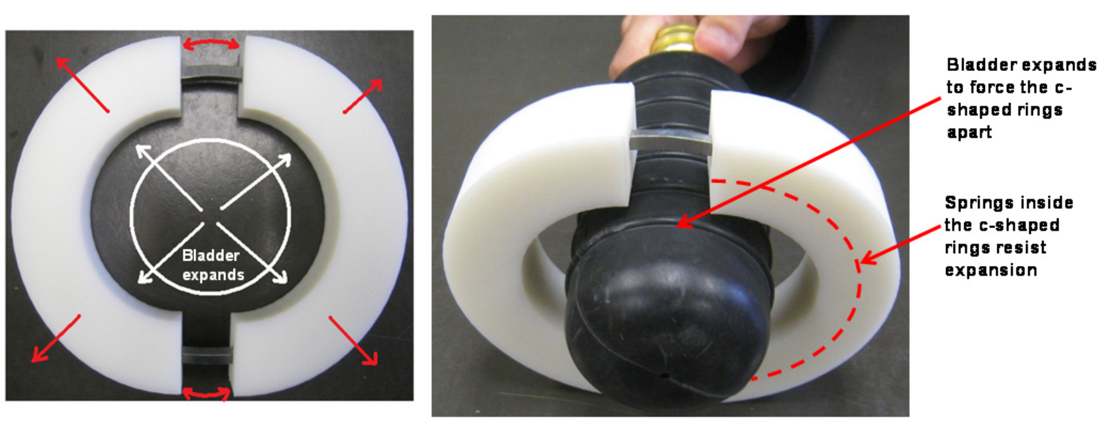


Figure 32: The prototype tests the concept's functional feasibility

Prototype testing helps assess the interaction between the parts of the expanding ring and its overall functional kinematic feasibility. The former refers to analyzing the relative motion between the moving parts, while the later checks for effective expansion and retraction of the expanding ring prototype. The bladder is pressurized with water and its expansion causes the composite ring to expand as desired. The composite ring also retracts to its original state once the pressure in the bladder is released.

Following the successful prototype tests, an analytical model of the expanding ring is built in Solid Works®. The model helps determine the design's geometrical and material specifications. A finite element analysis of the model evaluates the expanding ring's performance under the proposed working conditions and thereby assesses its structural integrity.

The dimensions of the c-shaped rings are dictated by the wellbore casing geometry. From the virtual model, the spring's extension requirements for deployment are also identified. This in turn helps determine the spring's length, material, and the spring constant. Normalized steel 4340 is chosen as the springs' material because it has properties similar to those of the material used in the springs that are currently used as the back-up seal. Since the springs in the new expanding ring concept do not face pressure forces unlike the currently used springs, this choice is easily justified.

Besides helping establish these properties of the composite ring, the virtual model also helps determine the deflection requirements for the c-shaped rings. Essentially, the c-shaped rings must deflect to ensure a seal with the wellbore casing, along the entirety of its circumference as seen in the Figure 33 below.

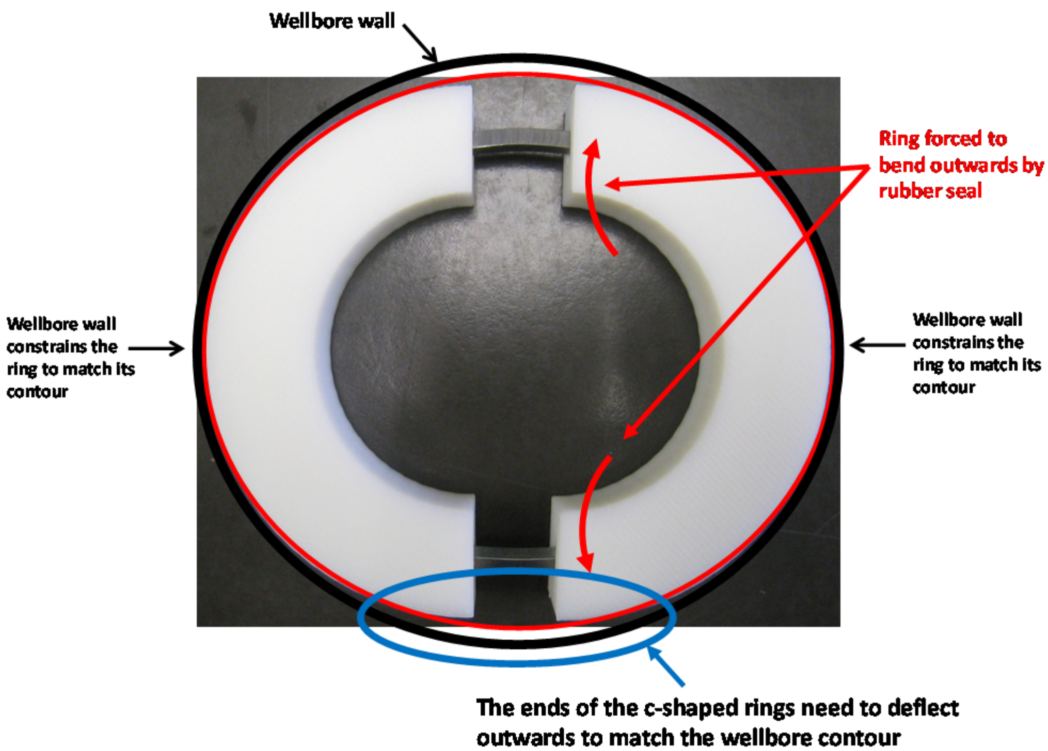


Figure 33: Ends of the c-shaped ring need to deflect towards the wellbore casing to ensure a seal along the entire circumference

Finite element analysis evaluates the c-shaped rings' ability to deflect as well as its ability to withstand the external fluid pressures. Therefore, the c-shaped rings are analyzed under two different test conditions: a one constrained face condition and a two constrained faces condition. For each test a stress-strain analysis and a deflection-deformation analysis are performed.

Test 1: Single constrained face

This test determines whether the ring can deflect sufficiently to seal the gap between the bridge plug and the wellbore without failure. The test conditions include a single constrained face and a uniform force that simulates the rubber seal pushing on the internal surface of the c-shaped ring as seen in Figure 34 below.

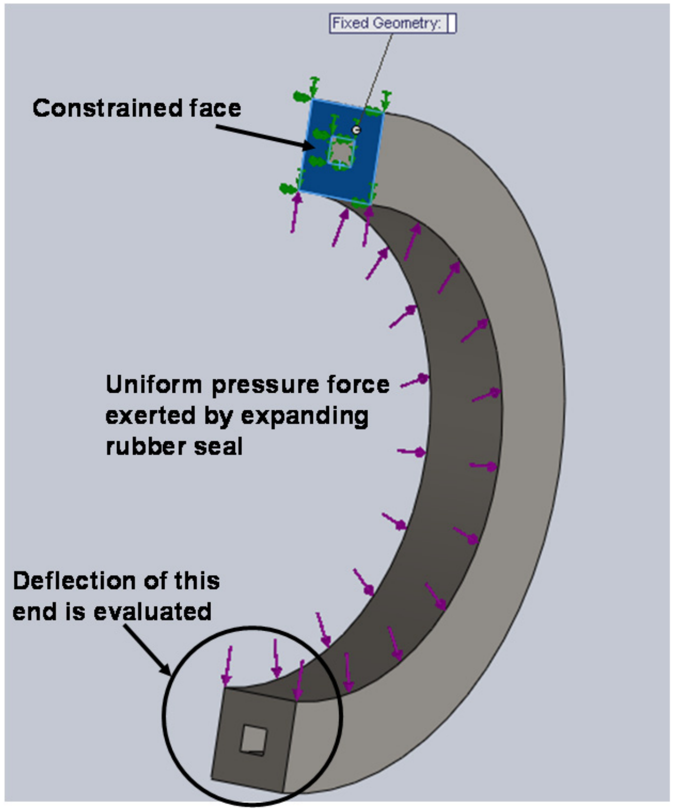


Figure 34: Single constrained face model helps evaluate the deflection of the c-shaped rings' ends

With regards to the c-shaped ring's deflection, there are two possible failure modes: the c-shaped ring's inability to deflect under the available expansion force or its inability to return to its original size once the applied force is removed.

Results from the analysis show that the force used to expand the currently used seal is sufficient to deflect the c-shaped ring by the desired amount. Secondly, this deflection is within the elastic limit of the chosen material, Normalized Steel 4340 as seen in Figure 35 below.

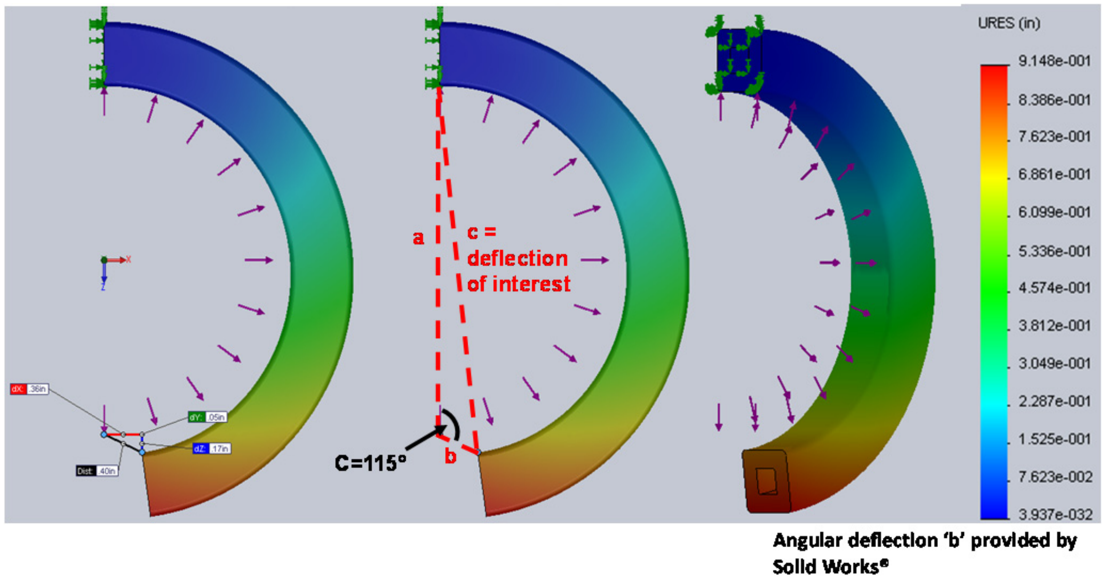


Figure 35: The deflection is evaluated using the Normalized Steel 4340 properties for the c-shaped ring

The true deflection of interest (shown as 'c') is calculated from 'b' and the angle 'C' using the triangle cosine formula: c2 = a2 +b2 – 2ab[cos C].

Test 2: Two constrained faces

This test reviews the ring's response to the specified loading conditions. To simulate the actual loading conditions, the c-shaped ring is constrained at two faces and a uniform pressure force acts on one of the surfaces as seen in Figure 36 below.

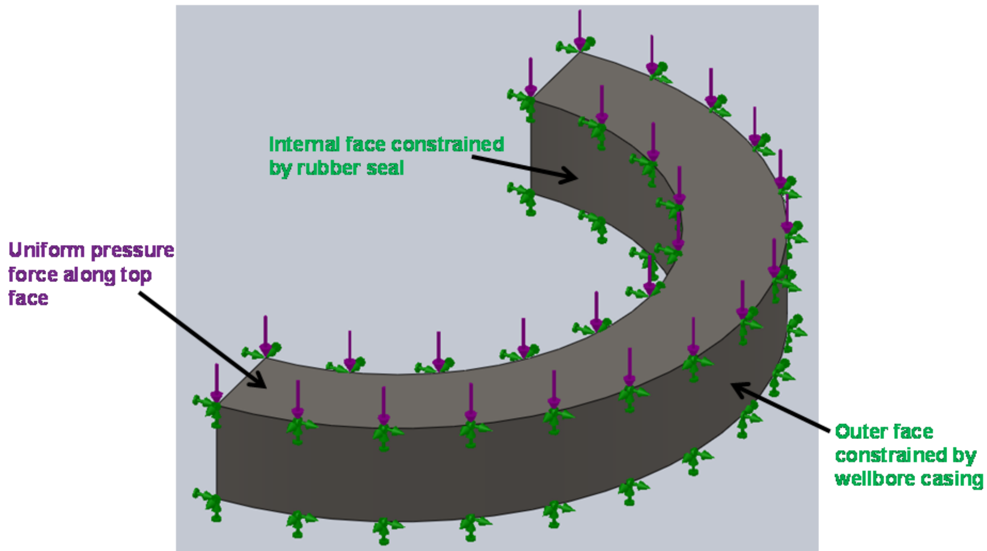


Figure 36: Setup to test ring's ability to withstand pressure forces

The green arrow constraint arrows on the inner surface represent the rubber seal forcing the ring to expand radially outwards. Green constraint arrows on the outer surface represent the wellbore casing that limits the ring's expansion. Thus, the rubber seal on the inside and the wellbore casing on the outside hold the c-shaped ring in place. Similarly, the purple arrows on the top surface represent the fluid pressure forces. The fluid pushes against the ring and forces it to slip causing instability in the seal.

The fluid pressure must not cause the ring to deform. This would constrain the internal spring's motion, as the hollow cavity would close on it. With the spring unable to move, the composite ring cannot retract. However, the analysis shows that the stresses experienced by the c-shaped ring under the specified loading condition are greatly below its yield strength and therefore the ring would not deform considerably as seen in Figure 37 below.

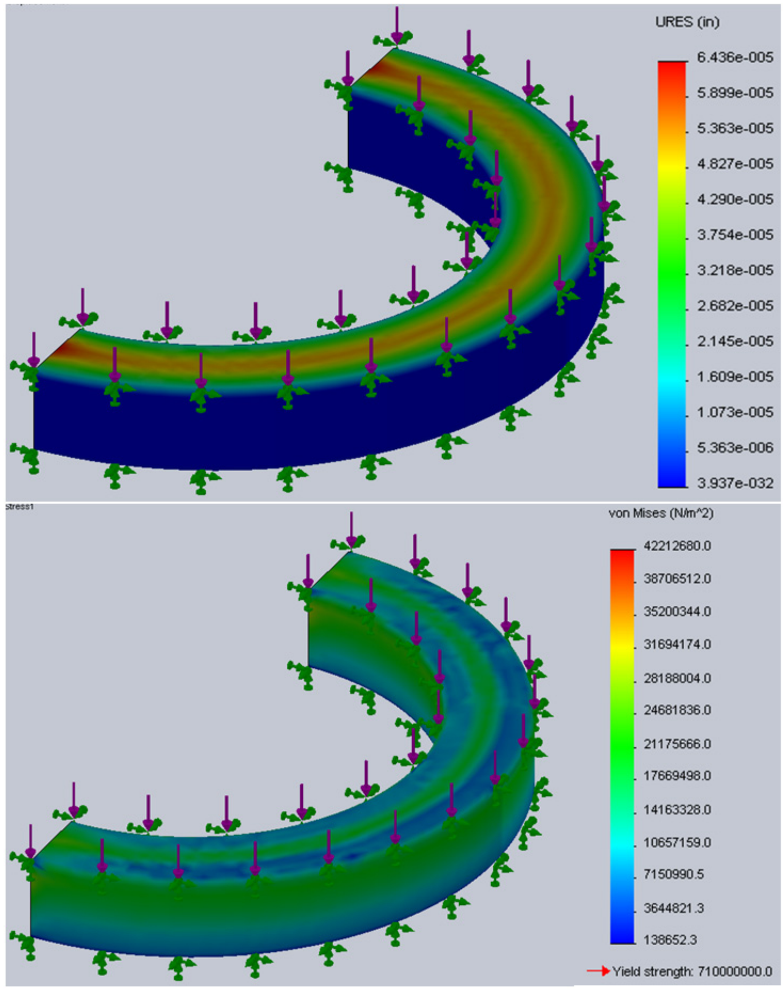


Figure 37: The normalized Steel 4340 c-shaped ring can sustain the stresses and deflections caused by the fluid pressure

These results show that the maximum stress and the maximum deformation (or deflection) for the c-shaped ring are within the acceptable limits for the chosen material, Normalized Steel 4340.

Results from the detailed analysis of the expanding ring concept are summarized below.

1. The internal springs are not load carrying members or do not have to provide any structural support and therefore can have a higher elasticity allowing for easier expansion and retraction of the ring.

2. The available expansion force is sufficient to deflect the c-shaped rings to create a seal along the entire circumference.
3. This deflection is within the elastic range of the selected material, thereby allowing the rings to return to their original state on deactivation.
4. The c-shaped steel rings are strong enough to withstand the external fluid pressures.

6.2.7 Case Study Overview

Reviewing the case study thus far, we have shown how the TRIZ and biomimetic design principles inspire solutions or concepts for a given design problem. Also, the conceptual solution obtained is shown to meet all the design problem's needs or requirements. Next, this TRIZ and biomimetic design principles inspired concept is compared against the other concepts developed by the team. A comparative analysis finds it to be the best of the designs developed by the team for the stated design problem. Subsequently, the design is thoroughly tested under operating conditions to simulate its successful operation.

This sequential progression from the inspiring biomimetic principles to the eventual evaluation of the final concept highlights the usefulness of the biomimetic design principles with regards to predetermined design goals. However, it is important to note that the assessment and concept evaluation is not presented to prove that the using the biomimetic principles results in the best possible solution for any design problem. Instead, the principles are simply presented as a tool that when used alone or with other idea generation tools can inspire designers to develop innovative and robust biomimetic products. Additionally, the same biomimetic design principles can inspire different product or solution ideas based on the individual designer's background and use of the principles.

7 VALIDATING THE METHOD: VALIDATION SQUARE

This section reviews the developed principle extraction methodology and case studies within the validation square framework. The validation square provides designers with a framework that helps validate a newly proposed design methodology. It guides the designer through the process of demonstrating the proposed method's usefulness with respect to some predetermined purposes. Here the method's purpose is twofold.

1. Effectively identify biomimetic design principles from the analysis of natural systems or biomimetic product pairs.
2. Show that the identified biomimetic design principles can help designers create innovative and robust candidate biomimetic engineering products or solutions.

The framework tests the proposed method's structural soundness and performance ability. Validating the method's structure based on qualitative measures confirms its proposed effectiveness. Similarly, validating the method's performance based on quantitative measures confirms its proposed efficiency. In this case, efficiency refers to the biomimetic design principles' ability to inspire innovative solutions or products. Figure 38 outlines the validation square framework used to validate a design method.

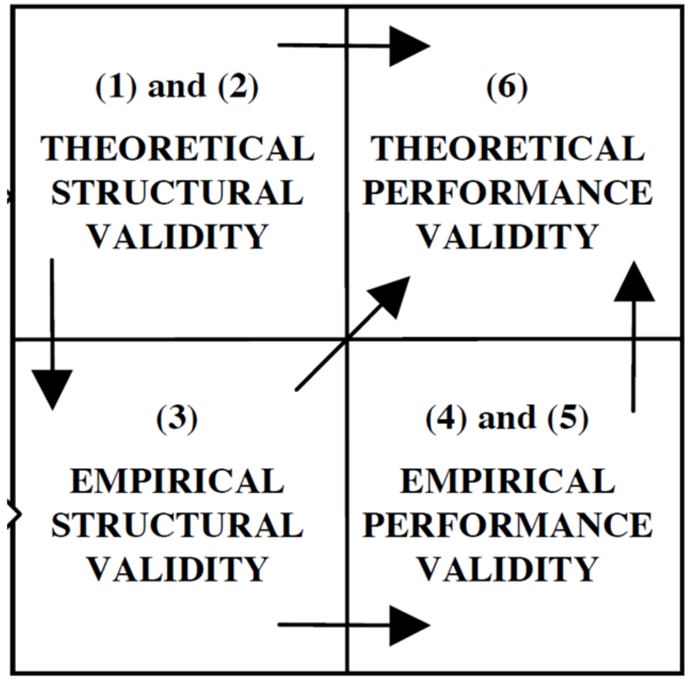


Figure 38: The validation square framework [37]

The numbers 1 through 6 represent an argument that can be accepted with regards to the proposed method. Therefore, to be considered valid under this framework a review of the proposed method must provide evidence that allows a designer to:

1. Accept validity of the individual constructs constituting the method
2. Accept the internal consistence of the way in which the constructs are put together in the proposed method
3. Accept the appropriateness of the example problems that will be used to verify the performance of the method
4. Accept that outcome of the method is useful with respect to the initial purpose for some chosen example problem
5. Accept that the achieved usefulness is linked to applying the method
6. Accept that the usefulness of the method is beyond the case studies

Arguments 1, 2, and 3 are evaluated using a qualitative review of the method's individual constructs and form the basis of the method's structural validation. Arguments 4, 5, and 6 are evaluated using quantitative measures to review the results from the case studies and form the basis of the method's performance validation. The following subsection describes this review and thereby confirms the proposed principle extraction method's validity.

7.1 Structural Validity

The principle extraction methodology incorporates five existing design tools or theories: functional modeling, morphological matrices, the theory of highly optimized tolerance, the function-behavior-structure representation, and a color-coding abstraction methodology. This subsection reviews these tools and theories with respect to three aspects.

First, each tool or theory is individually reviewed with regards to its theoretical basis, validity, and use. This critical analysis helps accept the individual tool or theory's soundness. Second, the way in which these individual methods are put together to make up the proposed principle extraction methodology is reviewed. This helps confirm and accept the methodology's logical internal structure and consistency. Last, the proposed case studies are reviewed to verify whether they test the methodology's usefulness with respect to predetermined goals. This establishes the appropriateness of the case studies.

Following this review and analysis, the proposed methodology's structural validity can be accepted [8]. The requisite reviews are presented in detail below.

7.1.1 Accepting Validity of the Individual Constructs Constituting the Method

Each tool or theory used in the proposed biomimetic principle extraction methodology is reviewed with regards to its theoretical basis, validity, and usefulness.

Functional modeling

Functional modeling is a process that enables the representation of a given system in terms of its functions, material flows, energy flows, and/or signal flows. At its theoretical basis is the notion of a function, which represents a relationship between the inputs and desired outputs of a system [39]. Pahl and Beitz note that in order to solve any problem or design any system, there is a need to clearly state a reproducible relationship between inputs and outputs [38]. Therefore, with regards to design problems a function is very useful and purposeful term that states the general relationship between the inputs and outputs. It is important to note that a function is an abstract representation of the system's task and is independent of specific solution concepts.

For complex systems, the overall task or function can often be decomposed into sub-functions connected through a set of material, energy, and/or signal flows. This decomposition is called a function structure or functional model [38, 39]. As an abstract, logical, and repeatable representation of a system, the functional model can help greatly in the design process specifically with regards to idea generation [39, 45]. Erden et al review functional modeling's widespread applications and use in various fields [12].

While functional modeling's usefulness is widespread, it is important to question its repeatability and uniqueness claims when investigating its validity. Experimental tests have shown that given a structured functional modeling method, different designers can produce repeatable functional models [40]. It is important to note, that having a formal structured functional modeling method enhances repeatability. This method relies on using a common language for functional modeling. Various efforts made in developing this common language are identified in [40]. This common unified language is called the Reconciled Functional Basis [19]. It provides a generic set of function and flow terms that enables the development of repeatable functional models for similar products.

In this research, the structured functional modeling method is used with the functional basis language to develop the requisite functional models. Therefore, based on its theoretical basis, structured methodology, and repeatability data, we can conclude that functional modeling is an acceptable construct or design tool.

Morphological matrices

The morphological matrix is an extension of the functional modeling process. It is a tool that helps with comparing and combining conceptual solutions during the product design process [39]. It is essentially, a listing of the various solutions for the product's sub-functions is a matrix format as seen in Figure 39 below.

Functions	**Solution methods**				
	1	2	⋯	⋯	m
F_1	S_{11}	S_{12}	⋯	⋯	S_{1m}
F_2	S_{21}	S_{22}	⋯	⋯	S_{2m}
⋮	⋮	⋮	⋯	⋯	⋮
⋮	⋮	⋮	⋯	⋯	⋮
F_n	S_{n1}	S_{n2}	⋯	⋯	S_{nm}

Figure 39: Basic format for a morphological matrix

Since it extends the use of a product's functional model for solution comparisons, it shares the same theoretical basis as that of the functional modeling process. It combines the notion of a product's function and/or sub-functions with conceptual solutions. These solutions can include existing conventional solutions that achieve the given function or new conceptual ideas developed by the designers to meet the given function. It provides a simple graphical representation that serves as a very useful idea generation tool during the design process [38].

To further investigate the validity of the morphological matrix approach, we must consider review its structure. There are different variants of the morphological matrix, but all of them list the product's functions in a single column. The rows then contain various solution approaches that meet the corresponding functional requirement. This structure's simplicity makes it easy to follow and effective.

Solution combinations and comparisons obtained using the morphological matrix depend on the individual problem and the designer's needs. Therefore, repeatability is not a relevant measure in this case. However, when combing various solutions for sub-functions to form a single system, it is important to ensure smooth energy, material, and/or signal flows throughout the system [38]. Additionally, Tinsley et al have shown the usefulness and effectiveness of using morphological matrices to compare natural system solutions to those of engineering systems [3].

In this research, a structured morphological matrix approach is used with the functional basis language to compare natural system and engineering system solutions. Therefore, based on its theoretical basis, structured methodology, and effectiveness shown through examples, we can conclude that the morphological matrix is an acceptable construct or design tool.

The Theory of Highly Optimized Tolerance (HOT)

Understanding the behaviors of complex interconnected systems is an important research topic. Behavior in terms of failures is specifically important due to the economic and environmental costs associated with their occurrence. Self-organized criticality (SOC) and the edge of chaos (EOC) theories predict power law models for failures in complex systems [43]. These theories are rooted in the idea that complexity arises as a consequence of bifurcations or dynamical instabilities. However, the HOT theory motivated by biological organisms and advanced engineering technologies is based on the view that complex systems are almost always intrinsically complicated. These systems include a large amount of built-in structure and redundancy [57]. Carlson and Doyle suggest that this makes engineered and biological complex systems behave in a reasonably predictable manner despite uncertainties in their environment. Therefore, the power laws in these systems are due to the trade-offs between yield, cost of resources, and tolerance to risks. As a consequence, the HOT theory is proposed to account for the tendency of interconnected complex systems to show robustness against designed-for uncertainties, while failing drastically against other uncertainties.

Carlson and Doyle state that HOT systems have four characteristic features that include: (1) high efficiency, performance, and robustness to designed-for uncertainties, (2) hypersensitivity to design flaws and unanticipated perturbations, (3) non-generic, specialized, structured configurations, and (4) power laws. They use percolation and sand pile models to validate the mechanism of HOT systems and highlight the contrast with self-organized criticality [1].

This research borrows the idea of a HOT system or HOT state to establish a context for the analysis of a given natural system or bio-inspired engineering system. This is because as stated earlier, a robust design with low failure rates within designed-for environmental uncertainties is a desirable system trait. The research then uses a highly optimized system's characteristic features as stated by Carlon and Doyle to define what is called a HOT characteristic.

This definition or description of a HOT characteristic helps the user identify characteristic features that make a given natural system or bio-inspired engineering system robust or highly optimized and tolerant. The term robust as used here relates to a product or design's ability to successfully accomplish its predetermined functions within its designed-for environment. This definition adds structure to the contextual analysis required in this research.

Therefore, on the basis of this added structure along with the theoretical basis and validation models of the theory, we can conclude that the HOT theory as used in this research is an acceptable construct.

Function-behavior-structure (FBS) representation

Umeda and Tomiyama propose a knowledge representational scheme for functions called the function-behavior-structure model. This scheme defines a system or design in terms of its function as an association of human intention and behavior in a hierarchical format [58]. The function-behavior-structure framework is used as a knowledge representation scheme that supports the conceptual design process.

The FBS framework builds on the established theoretical basis of a function and a functional decomposition. However, the framework emphasizes a hierarchical representation of a design object in terms of function.

Function, behavior, and structure form a knowledge representation scheme that can bridge the gap between human intention and physical behavior of systems at the conceptual design stage. The FBS framework is widely recognized as a tool used to effectively articulate the description of a system. Functional representation serves as an important means to capture the design activities and choices within the design process [45].

Owing to its various potential applications in the design process, designers have developed variations of the FBS model to support these needs. The different models add structure to the process and have been validated using example problems, reviews, and/or critical analyses [35, 46, 58, 59].

In this research however, the FBS framework is not used to model the natural system or biomimetic product pair under review. Instead, the FBS framework inspires the questions asked of the natural system or biomimetic product pair being examined for biomimetic design principles. In other words, questions regarding function, behavior, and structure are asked of the natural system or biomimetic product pair under consideration. Since, the FBS framework is used to capture the fundamental nature of a system; we can conversely state that it can be used to effectively explore or examine a system. Therefore, based on its theoretical basis, its recognition as a modeling framework, and the subsequent implication of its ability to investigate a system, we can accept the FBS framework's use as a construct in this research.

Developing transformation principles: Color-coded principle abstraction

Singh et al use an inductive and deductive process to develop design principles that help designers conceptualize transforming products [36]. The transformation design principles are identified from key design features and functional elements of transforming products. They define a transformation as an act of changing a state to facilitate new or enhanced functionalities.

Their combined research approach includes identifying principles for transformation from examples in nature, existing products, and patents (inductive approach), and from situations that would potentially require transforming products (deductive approach). From these inductive and deductive approaches, they identify characteristics and functions that exemplify device transformation. These characteristics are then abstracted into transformation design principles.

Sing et al use a structured four step procedure that requires reviewing, color-coding, and grouping the identified characteristics. This results in categorizing the characteristics into three fundamental transformation principles: "expand/collapse", "expose/cover", and "fuse/divide". Adding to this structured process, Singh et al also validate the sufficiency of the principles developed by comparing the number of new characteristics or potential principles exposed by each patent to the total cumulative characteristics or principles. They show that a majority of the principles are extracted in the first half of the patents analyzed and therefore suggest that their analysis of 41 patents has captured a high percentage of transformation principles.

The transformation principles are also applied to design for transformation by using a mind mapping approach to develop a list of possible transformation products. This illustrates the understanding of transformational design theory and the knowledge of transformation principles can help develop new transformational products. They also present a case study that illustrates the application of specific transformation principles.

In this research, there is similar need to abstract high-level or fundamental design principles from a set of characteristics identified from the analysis of biomimetic product pairs and natural systems. To meet this need, the research uses the reviewing, color-coding, and grouping procedure that helped develop the transformation design principles. Therefore, based on its structured approach and successful application in developing transformation principles, we can accept the abstraction procedure as a valid construct as used in this research.

7.1.2 Accepting the Internal Consistence of the Way in Which the Constructs are Put Together in the Proposed Method

This subsection reviews the way in which the individual design tools or theories are combined to form the proposed principle extraction methodology. The emphasis is on reviewing the methodology's internal structure, verifying the coherence of the information flow within the structure, and confirming that the individual constructs are used appropriately. An overview of the proposed principle extraction methodology is presented in Figure 40 below.

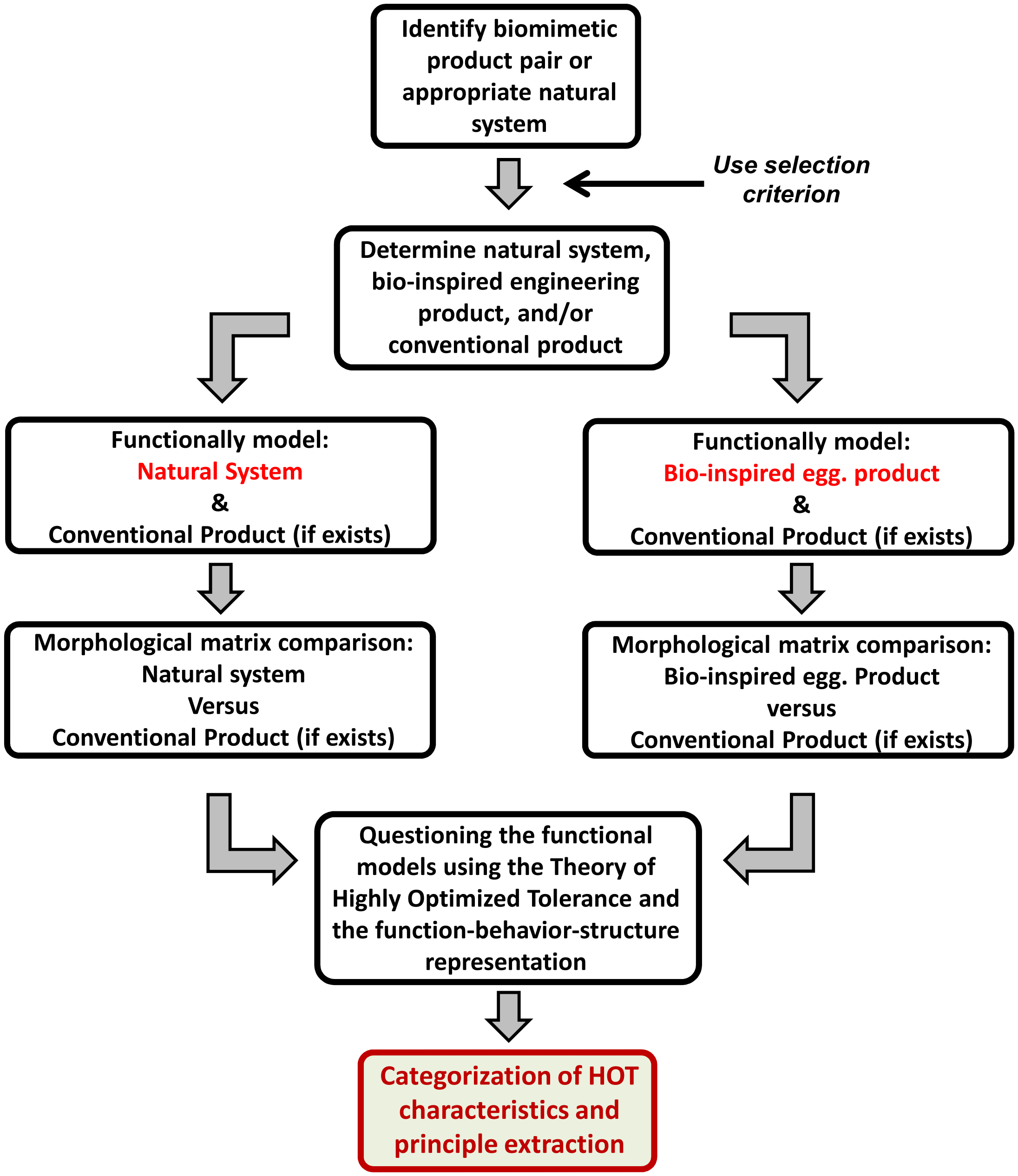


Figure 40: Overview of the principle extraction methodology

In terms of its structure, the proposed methodology has three important features. It is sequentially organized, coherent, and uses the individual design tools or theories in a manner that is consistent with their intended approach and application.

The organization sequence is dictated by the methodology's overall goal, which is to extract the key features and functional elements of natural systems or biomimetic product pairs and then abstract them into high-level fundamental design principles. A detailed list of criteria adds consistency to the natural system and biomimetic product pair selection process. This ensures that the system chosen for subsequent analysis has the potential to reveal characteristics that exemplify biomimetic design principles. Next, the methodology outlines a detailed procedure that helps functionally model the natural system, bio-inspired engineering product, and/or the conventional product under review. This procedure ensures the creation of accurate and repeatable functional models. Similarly, the method also outlines a procedure that helps compare different systems and products using a common morphological matrix format.

Further analysis on the systems under review includes questioning them using the theory of highly optimized tolerance. The methodology uses the established function-behavior-structure knowledge representation scheme as the basis for the questions asked of the systems. This ensures capturing the essence of the system in terms its key features, functional elements, structures, strategies, and/or behaviors. Finally, a structured review, color-coding, and grouping procedure helps abstract the identified characteristics into fundamental biomimetic design principles. This structured process leads to the effective abstraction of characteristics into high-level principles of similar hierarchy, scope, and type.

The methodology's sequential organization logically walks a designer through the analysis of a given natural system or biomimetic product pair. This logical analysis is achieved by suitably using the various design tools at the appropriate stages of the methodology. Hence, the methodology requires functionally modeling the given system before comparing its solution principles to other products and asking questions of it. This is in accordance with the need to maintain an abstract view of a system when functionally modeling it. Similarly, the methodology then uses the morphological matrix, the HOT theory, and the FBS framework to comprehensively analyze the given system. Again, the analysis is sequential to prevent inhibiting the potential effectiveness associated with using the individual methods. Therefore, this logical arrangement ensures that the given system is analyzed in a coherent manner.

Lastly, the methodology uses the individual design tools and theories as per their intended purpose. The functional modeling method is commonly used to represent a system's functionality in abstract terms without regard to the system's physical components. In this research, the methodology is used to represent both natural systems and engineering products. For natural systems, the engineering-to-biology thesaurus is used in concert with the functional basis to ensure consistency. Similarly, the morphological matrix is used in this research to compare the solutions of natural systems or bio-inspired products to those of engineering products. The research uses the HOT theory's definition of characteristic features and the FBS framework to examine the given system and identify the characteristics that make it robust. Finally, the methodology uses the abstraction procedure developed by Singh et al to abstract the identified characteristics into design principles.

Owing to the methodology's sequentially organized structure, its internal coherence, and its consistent use of design tools or theories, we can accept the validity of its internal consistence.

7.1.3 Accepting the Appropriateness of the Example Problems That will be Used to Verify the Performance of the Method

This research uses two case studies to evaluate and validate two different aspects of the work. The first case study assesses the developed methodology's effectiveness and repeatability in extracting principles from a natural system and a biomimetic product pair. Two undergraduate students, one a mechanical engineering student and the other a biology student use the methodology analyze two systems: a natural system and a biomimetic product pair. The author also investigates these systems using the same methodology. This allows for a comparison of the results leading to an understanding of the methodology's repeatability and effectiveness with regards to extracting or inferring principles.

The second case study highlights the usefulness of the developed biomimetic design principles themselves. In this case study, the biomimetic design principles are used to inspire a solution for an engineering design problem. The inspired solution is evaluated against the design requirements and also compared to other solutions developed without the biomimetic design principles. The analysis helps evaluate whether the biomimetic design principles can inspire novel candidate solutions or products that are innovative and robust.

The two case studies serve to test and validate both, the developed principle extraction methodology and the 'extracted' or developed biomimetic design principles. Therefore, we can accept the appropriateness of the example problems or case studies used to verify the performance of the proposed method.

7.2 Performance Validity

Having accepted the validity of the method's individual constructs, its internal structure, and the example problems used as case studies; this subsection reviews the method's application and evaluates the results obtained.

As part of the first case study, the principle extraction methodology is used to identify biomimetic design principles from two given systems. These principles are compared with those identified by the author from the same systems. The second case study involves using the biomimetic design principles to inspire a solution for an engineering design problem. This solution is compared with other designs developed using different concept generation methods.

Analyzing these results also reveals how the biomimetic design principles can inspire novel and effective solutions for engineering problems. Following this analysis, the proposed methodology's performance validity can be validated [37]. The requisite reviews are presented in detail below.

7.2.1 Accept That Outcome of the Method is Useful With Respect to the Initial Purpose for Some Chosen Example Problem

In this subsection, results of each case study are evaluated against the study's initial purpose. The first case study aims to compare the system characteristics identified by the author to those inferred by the students when using the same principle extraction methodology. In the second case study, the biomimetic design principles developed in this work are used to inspire a conceptual solution for a given design problem. The inspired concept is then evaluated against the four requirements outlined in the design problem.

Case study 1: Using the principle extraction methodology

This case study involved two students using the proposed principle extraction methodology to analyze a natural system and a biomimetic product pair. The chosen natural system is the cricket's flow sensor, while the biomimetic product pair is the cocklebur inspired Velcro® fastener and the cocklebur plant's seed. Before presenting the students with an overview of the two systems, the author analyzed both the systems using the principle extraction methodology. The purpose of the case study is to compare the characteristics identified by the author to those obtained by the students when using the same principle extraction methodology.

The students' analysis of the two systems using the principle extraction methodology led to the identification of characteristics of the systems that are in turn abstracted into biomimetic design principles. The results from a comparison of the characteristics identified by the author and the students are summarized in Table 12 below.

Table 12: Comparison of the characteristics identified from the analysis of a natural system and biomimetic product pair

System	**Analysis performed by**	**Total number of characteristics identified**	**Commonly identified characteristics**	**Differing characteristics**
Cricket's flow sensor	Author	2	2	1
	Student 1	4		
	Student 2	3		
Velcro® fastener & Cocklebur seed	Author	4	3	1
	Student 1	3		
	Student 2	3		

The following observations can be made from the results presented above and the detailed descriptions presented in the subsection: Case Study 1.

- Using the principle extraction methodology, the students extracted both the characteristics identified by the author for the cricket's flow sensor.
- Using the principle extraction methodology, the students extracted the three characteristics identified by the author for the cocklebur inspired Velcro® fastener.
- A single differing characteristic is identified when analyzing the natural system: the cricket's flow sensor. This is attributed to the students' consideration of the proposed bio-inspired system when answering the four questions outlined in the methodology. The principle extraction methodology is appropriately modified.
- A single differing characteristic is identified when analyzing the biomimetic product pair: the cocklebur seed and the Velcro® fastener. The author identifies this additional characteristic in a separate review process and it reflects properties of the natural system [7]. However, the methodology does not require asking

questions of the natural system when analyzing a biomimetic product pair. Therefore, the students are not expected to identify this specific characteristic.

Based on the comparison between the author's and the students' use of the principle extraction methodology, we can accept that the proposed methodology repeatedly and effectively extracts or identifies the requisite characteristics of a natural system or biomimetic product pair. A detailed review of the characteristics identified by the author and the students is presented in the subsection that describes the first case study in detail. It also includes a comparison of each identified characteristic.

Case study 2: Applying the biomimetic design principles

This case study required using the biomimetic design principles to inspire the design of a back-up seal. The sealing system used in the bridge plug consists of a primary seal and a secondary or back-up seal. An expandable and retractable high strength rubber element provides the primary sealing function, while a stiff metallic spring on either side of this rubber element provides the back-up sealing function. Owing to problems with the existing back-up seal design, the team is required to design a new back-up seal that solves these issues and thereby meets the four design requirements. Therefore, in this case the four design requirements represent the initial purpose of the chosen example problem.

A detailed analysis of the biomimetic design principles inspired expanding ring design is provided in the earlier subsections of this work. An overview of the concept is presented in Figure 41 below.

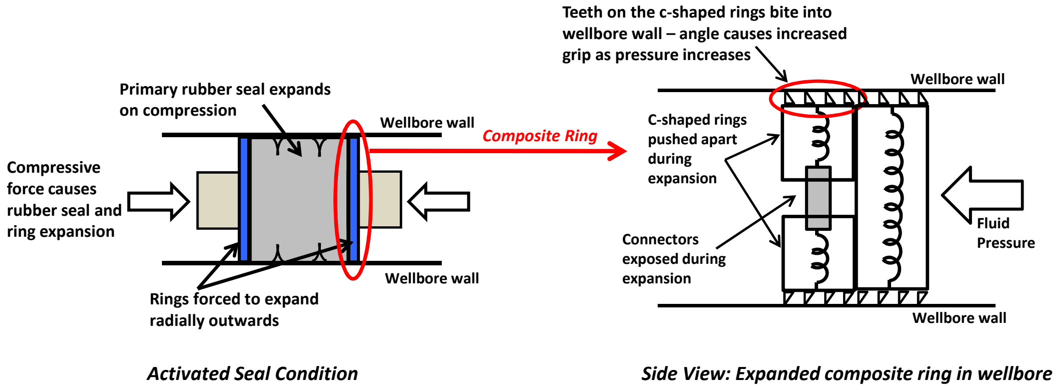


Figure 41: The expanding ring concept overview

The expanding ring's design is evaluated against the four design requirements below.

1. *The back-up seal must activate under compression and deactivate under tension as with the existing design.*

   Like the original back-up seal design, the expanding ring uses springs to allow for radial expansion and retraction under compression and tension along the perpendicular axis. Therefore, the concept meets the deployment and removal needs.

2. *The back-up seal must be retractable to ensure easy removal if wellbore needs to be reopened.*

   The internal springs force the composite expandable ring to close when the compressive force (along the perpendicular axis) on the ring is relaxed. Therefore, it meets the requirement to be retractable.

3. *The new back-up seal must provide improved structural support to the rubber seal without compromising its sealing integrity.*

   Two expandable rings on either side of the primary rubber seal provide the primary rubber seal with the required structural stability. The strong c-shaped rings protect the internal springs as well as the rubber from the well's pressurized fluid. This design provides the necessary structural support and therefore meets the stated requirement.

4. *When deployed together the new back-up seal and rubber seal must not leak.*

   For the original design with springs molded into the rubber seal, leakage was caused due to tears in the rubber at the spring-rubber interface. This is because the steel springs and the rubber seal have different expansion characteristics. Additionally, as the springs expand gaps between the steel windings leave the rubber exposed to the pressurized fluid.

   In contrast, the springs in the expandable ring concept are housed inside solid c-shaped rings. Since these springs do not contribute to the structural strength, they are not very stiff and therefore easy to stretch. As a result, the expandable ring expands easily with the rubber seal and the disparity between the expansion characteristics is reduced. This prevents the primary rubber seal from any damage and therefore meets the need to provide a tight seal.

Based on the design's ability to meet all the initial design needs of the back-up seal design, we can accept the developed method's usefulness with regards to the second case study. It is important to note that this work also compared the expanding ring concept with other designs developed using different concept generation methods. A detailed overview of the comparison and analysis is presented in the earlier subsection that describes the second case study in detail.

7.2.2 Accept That the Achieved Usefulness is Linked to Applying the Method

In this subsection, the results for each case study are traced back to the use of the proposed principle extraction methodology. This shows that the achieved usefulness of the case studies' results is tied to the application of the proposed methodology.

In the first case study, each student works through the principle extraction methodology step by step to analyze a natural system and a biomimetic product pair. This logical sequence illustrates how the steps of the methodology help the students and the author identify the system's underlying characteristics. For the second case study, different biomimetic design principles inspire different features of the developed concept. Linking the design principles to the concept's features that help it meet the design requirements shows how applying the biomimetic design principles can inspire innovative designs.

Case study 1: Using the principle extraction methodology

This case study tests the proposed principle extraction methodology's effectiveness and repeatability in extracting design principles from natural systems and biomimetic product pairs. Two students use the principle extraction methodology to analyze a natural system and a biomimetic product pair for characteristics that can be abstracted into biomimetic design principles. The author also analyzes the same systems using the principle extraction methodology to identify the underlying characteristics.

A comprehensive description of the case is presented in an earlier subsection: Case Study 1. It includes a detailed documentation of each student's use of the principle extraction methodology. In other words, each student works through the individual steps in the principle extraction methodology and thereby identifying the underlying characteristics of the system under analysis. The final step of the methodology requires the students to answer questions of the given system in the context setup by the previous steps.

Based on each student's step by step use of the methodology and the subsequent review, we can accept that the resulting system characteristics identified by each student and the author are a result of using the principle extraction methodology. Therefore, we can state that the results' achieved usefulness is linked to applying the biomimetic design principle extraction methodology.

Case study 2: Applying the biomimetic design principles

This case study uses the biomimetic design principles to inspire a solution for an engineering design problem. The developed concept is called the expanding ring back-up seal design and it is inspired by a combination of the TRIZ and biomimetic design principles. The different principles inspire different features of the concept. These features in turn help the concept meet its design requirements as shown in the subsection above. A summary of the design requirements, the concept's features that help it meet these requirements, and the corresponding inspiring principles are presented in Table 13 below.

Table 13: Overview of the biomimetic principles and the concept's features they inspire

Inspiring biomimetic design principle	**Concept's inspired feature**	**Design requirement met**
Composite structures: Make single part from two or more parts with distinct material properties and functionalities.	The expanding ring consists of three distinct parts: two hollow c-shaped steel rings, two steel connectors, and two metallic springs.	Back-up seal must activate under compression and deactivate under tension Back-up seal must be retractable
Environmental interaction: Use materials and/or energy from the environment to help the product/system accomplish its function.	The c-shaped rings' toothed outer surface anchors into the wellbore casing wall, thereby leveraging the strength of the rigid casing (environment) to resist pressure forces.	Back-up seal must provide structural support and maintain rubber seal's integrity
Substitute discrete self-similar features in place of a single feature used to achieve a critical function.	Two identical expanding rings replaced the single expanding ring to be placed on either side of the primary rubber seal, thereby closing the gap exposed on expansion when only one ring is used.	Back-up seal and rubber seal composite must not leak

Based on the evident progression from the inspiring biomimetic principles, to the concept's inspired features, and its subsequent evaluation against the design requirements, we can accept that the design's achieved usefulness is linked to applying the biomimetic design principles. A detailed description of the individual inspiring principles and the concept's resulting features is presented in the case study 2 subsection earlier.

7.2.3 Accept That the Usefulness of the Method is Beyond the Case Studies

Having critically reviewed the methodology's individual constructs and evaluated its performance through case studies, we have verified the methodology's structural validity and its performance. However, the usefulness of the methodology is beyond the scope of this work. Without a documented account of the methodology's application in various scenarios over time and their subsequent results, one cannot successfully confirm its usefulness.

8 COMPARING BIMIMETIC DESIGN PRINCIPLES, TRIZ, AND BIOTRIZ

Today's designers have access to various idea generation tools. The biomimetic design principles presented here also serve as an idea generation tool that helps designers create innovative nature inspired solutions. As a tool the biomimetic design principles are similar to the TRIZ and BioTRIZ methods in their underlying concept and implementation. This subsection reviews the three methods or tools comparatively to highlight the differences and similarities between them.

8.1 TRIZ and BioTRIZ

The Theory of Inventive Problem Solving (TIPS/TRIZ) is commonly used in the design process as an idea generation tool. Developed by Genrich Altshuller and his colleagues, it was proposed as a problem solving and analysis tool derived from studying the patterns of invention in around 3 million engineering patents [32]. However, the most widely used tool from the TRIZ methodology is the contradiction matrix. From the patent review, Altshuller et al identified 40 principles that solved a common set of engineering conflicts. These principles are placed in the contradiction matrix that serves as a look-up tool. Essentially, each row and column of the 39x39 matrix represents one of the 39 general engineering conflict parameters or factors identified. Thus, a designer looking for inspiration must state his/her design problem as a conflict between any two of the 39 engineering parameters. Then looking up the contradiction matrix with these parameters identifies a cell that contains the inventive principles that could solve the given conflict.

However, Bogatyreva et al suggest that the 39 engineering parameters that make up the contradiction tool are not comprehensive enough [33]. They claim that the parameters do not effectively represent contradictions from novel fields of technology or other emerging field like biochemistry and biology. Based on an analysis of 500 biological phenomena, Vincent and Bogatyreva et al explain that the distribution of the 40 inventive principles in the TRIZ contradiction matrix does not reflect biology's solution strategies to various problems.

After studying the TRIZ matrix for common patterns, they reorganize the contradiction matrix and redistribute the principles. The former includes classifying the 39 engineering conflict parameters in 6 operation fields: substance, structure, energy, information, space, and time. According to Vincent et al these fields can define all actions with any object [5]. Therefore, the 39 parameters are reduced to 6 operational fields and the new construction for the TRIZ matrix is called the PRIZM matrix seen in Table 14 below.

Table 14: PRIZM matrix derived from standard TRIZ [5]

FIELDS	Substance	Structure	Space	Time	Energy	Information
Substance	6, 10, 26, 27, 31, 40	27	14, 15, 29, 40	3, 27, 38	10, 12, 18, 19, 31	3, 15, 22, 27, 29
Structure	15	18, 26	1, 13	27, 28	19, 36	1, 23, 24
Space	8, 14, 15, 29, 39, 40	1, 30	4, 5, 7-9, 14, 17	4, 14	6, 8, 15, 36, 37	1, 15-17, 30
Time	3, 38	4, 28	5, 14, 30, 34	10, 20, 38	19, 35, 36, 38	22, 24, 28, 34
Energy	8, 9, 18, 19, 31, 36-38	32	12, 15, 19, 30, 36-38	6, 19, 35-37	14, 19, 21, 25, 36-38	2, 19, 22
Information	3, 11, 22, 25, 28, 35	30	1, 4, 16, 17, 39	9, 22, 25, 28, 34	2, 6, 19, 22, 32	2, 11, 12, 21-23, 27, 33, 34

The second part of their transformation of TRIZ, Vincent et al re-arrange or redistribute the TRIZ principles in the PRIZM matrix to better reflect the way in which nature solves specific contradictions. This new matrix is called the BioTRIZ matrix and is presented in Table 15 below.

Table 15: BioTRIZ: PRIZM matrix derived from biological effects [5]

FIELDS	Substance	Structure	Space	Time	Energy	Information
Substance	13, 15, 17, 20, 31, 40	1-3, 15, 24, 26	1, 5, 13, 15, 31	15, 19, 27, 29, 30	3, 6, 9, 25, 31, 35	3, 25, 26
Structure	1, 10, 15, 19	1, 15, 19, 24, 34	10	1, 2, 4	1, 2, 4	1, 3, 4, 15, 19, 24, 25, 35
Space	3, 14, 15, 25	2-5, 10, 15, 19	4, 5, 36, 14, 17	1, 19, 29	1, 3, 4, 15, 19	3, 15, 21, 24
Time	1, 3, 15, 20, 25, 38	1-4, 6, 15, 17, 19	1-4, 7, 38	2, 3, 11, 20, 26	3, 9, 15, 20, 22, 25	1-3, 10, 19, 23
Energy	1, 3, 13, 14, 17, 25, 31	1, 3, 5, 6, 25, 35, 36, 40	1, 3, 4, 15, 25	3, 10, 23, 25, 35	3, 5, 9, 22, 25, 32, 37	1, 3, 4, 15, 16, 25
Information	1, 6, 22	1, 3, 6, 18, 22, 24, 32, 34, 40	3, 20, 22, 25, 33	2, 3, 9, 17, 22	1, 3, 6, 22, 32	3, 10, 16, 23, 25

The process used to arrive at this matrix is not clearly outlined by Bogatyreva and Vincent et al [5, 33]. However, after analyzing 500 biological phenomena they claim that nature uses the same 40 inventive principles to solve problems; but the difference is that nature does not use the same principles to solve the same conflicts. In other words, nature and engineering use different solution principles for the same conflicting parameters.

8.2 Comparisons with Biomimetic Design Principles

This research presents a methodology used to extract biomimetic design principles from the analysis of a natural system or a biomimetic product pair. Like TRIZ and BioTRIZ, the developed biomimetic principles serve as an idea generation tool. However, they are different in two important ways. The first difference between the two sets of principles is the source they are obtained from. The second difference is in their presentation and in turn application for idea generation. Each difference is elaborated on in the following subsections.

8.2.1 Different Sources Used for the Principles

As mentioned earlier, the TRIZ principles were identified from an analysis of over 3 million patents. This extensive analysis of engineering patents indicates that the 40 TRIZ principles have their roots in the 'engineering domain'. In other words, Altshuller et al indentified inventive or creative engineering solutions employed by the different patents and abstracted them into principles [9]. BioTRIZ modifies the TRIZ matrix but maintains the same principles to solve different conflicts or problems. Their analysis of 500 biological phenomena showed that the 40 TRIZ principles (identified from studying engineering patent databases) were used by nature to solve design problems or conflicts.

The biomimetic design principles presented in this research are identified or extracted from a different source. These principles are identified from the analysis of natural systems (with potential engineering applications) and existing biomimetic product pairs. This is not to say that the TRIZ and BioTRIZ principles are inaccurate or inadequate. Rather, this research proposes that like the TRIZ principles identified from analyzing engineering patents, one could identify principles from nature or biology. Therefore, the biomimetic design principles focus on leveraging nature's novel and innovative solution strategies for engineering applications.

While Vincent and Bogatyreva et al mention that the TRIZ principles are also used in nature, they do not claim that the 40 principles are comprehensive and therefore represent all of nature's solution strategies. In fact, some of the biomimetic design principles identified from the analysis of natural systems and biomimetic product pairs in this research were found to closely resemble some of the TRIZ principles. This underlines and supports the Vincent et al hypothesis. On the other hand, this research methodology also identified biomimetic design principles that do not resemble any of the TRIZ principles suggesting that there is more to learn from nature. These new principles represent natural solution strategies that have not been visible in engineering designs of the past and can potentially help inspire innovative biomimetic engineering solutions.

8.2.2 Different Presentation and Application Method

Both the biomimetic design principles and the TRIZ (or BioTRIZ) principles serve to inspire innovative solutions to design problems. The TRIZ principles are presented in a look-up matrix format and are best used when the design problem is represented as a conflict between any two of the 39 conflict parameters. Similarly, BioTRIZ is also a look-up matrix, but unlike TRIZ it uses only 6 operational fields to look-up the required principles. The 39 conflict parameters from TRIZ are classified into the 6 operational fields: substance, structure, energy, information, space, and time. These 6 fields describe all actions with any object. However, in terms application both the matrices are very similar. In other words, the designer is still required to state the problem in terms of conflicts or contradictions that in turn identify principles from the look-up matrix.

The biomimetic design principles on the other hand are not presented in a matrix format suitable to looking up conflicting parameters. While in BioTRIZ the principles are classified into 6 operational fields based on the mantra: things to things somewhere, the biomimetic principles are classified into super groups based on the solution strategies they represent. Unlike the 6 operational fields, the super groups proposed here are not comprehensive and do not attempt to classify the actions related to an object in space. Rather, the super groups classify the nature inspired principles based on their solution strategies and are stated in systems level and/or parts level terminology. Like the conflict parameters, the super groups serve to guide and direct designers in using the biomimetic principles. Essentially, a design problem's attributes determine the super groups whose principles the designer must review for potential solutions. These attributes include specific needs of a design problem's solution or specific constraints on the design problem.

Having highlighted the differences between the biomimetic design principles, TRIZ, and BioTRIZ it is important to note that all methods serve a common purpose: to inspire innovative solutions for design problems. Vincent et al propose using BioTRIZ and TRIZ together to bridge the gap between nature and engineering. The biomimetic design principles offer nature inspired solution strategies to designers with little knowledge about biology required. In short, the three tools can be used separately or together to help designers create innovative solutions or products.

As mentioned earlier, a review of the identified principles revealed a similarity between a few of the biomimetic design principles and a few of the 40 TRIZ principles. While the goal of this research is to find nature's novel solution principles for engineering applications, this finding suggests that both nature and engineering use certain common solution strategies. Table 16 below shows he biomimetic design principles and TRIZ principles that are similar.

Table 16: Common biomimetic design principles and TRIZ principles

Design principles common to TRIZ and Biomimetic Design Principle Set	
Biomimetic Design Principles	**TRIZ Principles**
Composite: Make single part from two or more parts with distinct material properties and functionalities.	Composite materials: Change from uniform to composite or multiple materials
Substitute discrete self-similar features in place of a single feature used to achieve a critical function.	Segmentation: Divide an object into independent parts; increase the degree of fragmentation or segmentation
Use static and/or dynamic structures to replicate (or substitute) the natural environment that optimizes the product/system's performance.	Dynamics: Allow or design the characteristics of an object, external environment, or process to change to be optimal or to find an optimal operating condition Local quality: Change an object's structure from uniform to non-uniform, change an external environment or external influence from uniform to non-uniform; Make each part of an object function in conditions most suitable for its operation
Multi-functionality: Make the same part perform two or more distinct functions.	Universality: Make a part or object perform multiple functions; eliminate the need for other parts
Prevention over correction: Build preventive functionality into the product/system in place of reactive or corrective functionality to help achieve an overall function.	Preliminary action: Perform, before it is needed, the required change of an object either fully or partially Beforehand cushioning: Prepare emergency means beforehand to compensate for the relatively low reliability of an object
Use part(s) or feature(s) that is sacrificed after its functionality is achieved.	Cheap short-living objects: Replace an inexpensive object with a multiple of inexpensive objects, comprising certain qualities (such as service life, for instance) Intermediary: Use an intermediary carrier article or intermediary process. Merge one object temporarily with another (which can be easily removed)

Since BioTRIZ essentially uses the same TRIZ principles redistributed into 6 operational fields that classify the 39 conflict parameters, it is logical to state that the similarity holds true for these principles when used with BioTRIZ. The subsection below presents a simple review aimed at verifying whether the developed biomimetic principles hold true in the context of the BioTRIZ matrix.

8.3 Correlating the Biomimetic Design Principles to BioTRIZ

As stated earlier, Vincent et al. mention that nature uses the same TRIZ principles to solve different design conflicts. This subsection reviews the common TRIZ and biomimetic design principles within the context of the BioTRIZ conflicts they solve. The goal is to verify whether the biomimetic design principles (only those obtained from natural systems) reflect nature's solution approaches to conflicts as presented in the BioTRIZ matrix. This review process is graphically presented in Figure 42 below.

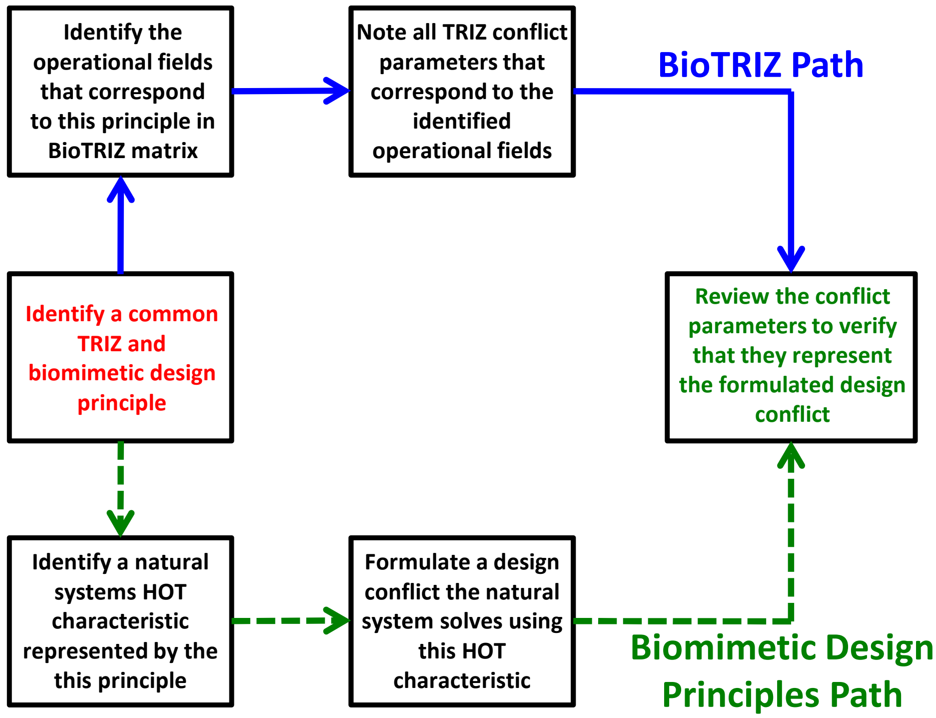


Figure 42: Reviewing the biomimetic principles in the context of the BioTRIZ matrix

For each common principle identified only a natural system HOT characteristic it represents is considered for this review. This is because BioTRIZ represents nature's solution strategies and not bio-inspired engineering products' solution strategies. In contrast, the biomimetic principles draw on HOT characteristics from both natural systems and bio-inspired engineering products.

This review process is repeated for all the principles that are common to the TRIZ matrix as well as the biomimetic design principle set. Table 17 below presents each common principle's HOT characteristic, its operational fields and TRIZ conflicts, and the design conflict it solves.

Table 17: Comparing the common principles' solution strategies with its BioTRIZ operational fields

Common principle	Characteristic	BioTRIZ operational fields	Natural system
Biomimetic Principle: Composite material **TRIZ principle #40**: Composite material	The composite (rigid foam sandwiched by keratin protein) structure gives the toucan beak its lightweight and high strength.	Energy (*Strength*) v/s Substance (*Weight of object*)	The toucan's strong beak is useful for foraging and defense, while its low density is essential for its ability to fly.
Biomimetic Principle: Discrete self-similar features **TRIZ Principle #1**: Segmentation	The discrete denticles (scales) on the shark's skin reduce drag.	Energy (*Loss of energy*) v/s Space (*Shape*)	The conflict represents the shark's need to reduce drag (or the loss of energy) without changing its body shape.
Biomimetic Principle: Provide optimal environment **TRIZ Principle 15**: Dynamics **TRIZ Principle 3**: Local Quality	N/A – No natural system characteristics identified; only bio-inspired system characteristics identified.	N/A	N/A
Biomimetic Principle: Multi-functionality **TRIZ Principle 6**: Universality	The nanoscale hair-like structures (setae) on the gecko's foot facilitate adhesion as well as self-cleaning.	Information (*Adaptability or versatility*) v/s Energy (*Loss of energy*)	The gecko's feet must use minimal energy to ensure attaching to various surfaces with or without dirt particles on them.
Biomimetic Principle: Prevention over correction **TRIZ Principle 10**: Preliminary action **TRIZ Principle 11**: Beforehand cushioning	The lotus' strategy is to prevent the accumulation of dirt on its surface rather than react after the dirt has been accumulated.	Time (*Duration of action of object*) v/s Energy (*Loss of energy*)	The lotus must use minimal energy to continually maintain a clean surface.
Biomimetic Principle: Use sacrificial part **TRIZ Principle 24:** Intermediary **TRIZ Principle 27:** Cheap short-living object	The plant uses an intermediate (abscission) zone to facilitate the separation of parts	Substance (*Loss of substance*) v/s Structure (*Stability of object's composition*)	The plant must remove damaged parts (to prevent the infection from spreading) without harming the surrounding regions.

The review shows that the natural system characteristics that exemplify the biomimetic design principles effectively represent nature's solution strategies as captured in BioTRIZ. This is because the natural system HOT characteristic represented by the biomimetic design principle is a solution to the design conflict called out in the BioTRIZ matrix. Additionally, this found to be true for all the principles common to the TRIZ matrix and the biomimetic design principle set. This implies that the biomimetic design principles abstracted from natural systems' HOT characteristics agree with BioTRIZ and represent nature's solution strategies.

9 CONCLUSIONS

Many researchers believe that the emerging area of biomimetic design has the potential to help designers meet the need for robust, innovative, and reliable products with diverse customer needs. Through years of evolution, nature has solved many important design problems and optimized those solutions for their respective environments. Therefore, there is a desire to deliberately leverage these optimized and robust solution strategies to develop new engineering products or solutions.

As with any emerging field, there are numerous problems associated with developing methods that successfully leverage biological knowledge to create biologically inspired engineering designs. Two important problems are an engineering designer's limited knowledge of biology and the differences in engineering and biological terminologies. This thesis presents a new design tool that addresses these two problems. It can help designers develop candidate bio-inspired engineering products or solutions for a given design problem.

This research develops set of high-level and abstract biomimetic design principles that can help designers create innovative and robust candidate biomimetic products or solutions. It also presents a principle extraction methodology that helps investigate a natural system or biomimetic product pair for the inherent design principles that underline the given system's robustness.

The principle extraction methodology incorporates and integrates five existing design tools, theories, and methods in a structured manner. The design tools or theories used in the methodology are function modeling, morphological matrices, the theory of highly optimized tolerance, the function-behavior-structure representation, and a color-coding abstraction methodology. As part of this research, the principle extraction methodology is used to examine 23 bio-inspired product pairs and natural systems for biomimetic design principles.

We propose that these biomimetic design principles, presented with facilitators can help designers develop candidate bio-inspired engineering solutions or products for design problems. Two case studies demonstrate the use of the principle extraction methodology and the biomimetic design principles.

In the first case study, two undergraduate students use the principle extraction methodology to extract or infer characteristics from a natural system and a biomimetic product pair. These are then compared to those identified by the author using the same systems and methodology. A correlation between the students' results and the author's results demonstrates the proposed principle extraction methodology's effectiveness and repeatability with regards to inferring system characteristics that exemplify the inherent biomimetic design principles.

In the second case study, the developed biomimetic design principles are used to inspire a solution for an engineering design problem. This solution is compared with other designs developed using different idea generation methods. The evident progression from the inspiring principles, to the concept's inspired features, and its subsequent evaluation against the design requirements shows that the design's achieved usefulness is linked to applying the biomimetic design principles. However, these principles can help inspire different candidate solutions when used by different designers.

In addition to the case studies, this research uses the Validation Square framework to evaluate the proposed principle extraction methodology and the identified biomimetic design principles. The framework helps validate the method's structure based on qualitative measures to confirm its effectiveness. Similarly, it helps validate the method's performance based on quantitative measures to confirm its proposed efficiency. In this case, efficiency refers to the biomimetic design principles' ability to inspire innovative candidate solutions or products.

Lastly, the biomimetic design principles are compared to the TRIZ principles and the BioTRIZ matrix. Similar to TRIZ and BioTRIZ, the biomimetic principles serve as an idea generation tool. However, TRIZ and BioTRIZ differ from the biomimetic design principles in two important aspects. First, the two sets of principles are obtained from different sources. Second, their presentation and method of application differ, possibly leading to different inspirations.

A comparison of the principles found that a subset of the biomimetic design principles are similar to a few of the TRIZ principles. This similarity suggests that both nature and engineering use certain common solution strategies. It also suggests that there is more we can learn from nature.

The work also included verifying whether the biomimetic design principles obtained solely from natural systems reflect nature's solution approaches to conflicts as predicted by the BioTRIZ matrix. A review showed that the natural system characteristics that exemplify the biomimetic design principles actually represent nature's solution strategies as captured in BioTRIZ. This was found to be true for all the principles common to TRIZ and the biomimetic design principle set.

10 FUTURE WORK

With regards to future work, the research would benefit from using the proposed methodology to examine or investigate additional natural systems and biomimetic product pairs for biomimetic design principles. This exercise could reveal nature's unknown solution strategies that, in turn help create innovative and robust bio-inspired engineering solutions.

Through TRIZ designers leverage the solution strategies prevalent in patented designs. Designers can similarly leverage nature's solution strategies through the biomimetic design principles. It is therefore important to examine a larger number of natural systems and biomimetic product pairs. With a structured and effective principle extraction methodology, different users can implement this examination or investigation.

The validation square analysis and the case studies presented in this work help demonstrate the methodology's effectiveness and the principles' usefulness. Another possibility is to conduct a larger experimental study that involves multiple subjects and scenarios to further test the method.

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APPENDIX

SECTION I:

This research involved identifying biomimetic design principles from the analysis of 23 natural systems and/or biomimetic systems. Subsection IV of the Appendix includes a description for each of the 23 systems. The underlying HOT characteristics identified from the analysis of the systems as seen in Table 18 below.

Table 18: HOT characteristics identified from the analysis of 23 natural and biomimetic systems

No.	Biomimetic product	Conventional product	Difference in strategies	Characteristics of biomimetic product	Characteristics of biological system
1	Inchworm inspired linear actuator: Such actuators consist of a flexible material connecting two clamps/brakes that attach to a shaft or guide rails. Electrical signals direct the breaking and releasing of the front and rear clamps to move the actuator a single step at a time.	Linear actuators: In contrast to the inchworm inspired linear actuators, conventional actuators use transformation to convert non-linear motion into linear motion. As a result these complex devices have a lower accuracy and a higher potential for failure.	The biomimetic product uses a flexible body to provide linear motion in contrast to conventional actuators that convert non-linear motion into linear motion.	1. The inchworm inspired actuator eliminates the need for transformations between non-linear and linear motion with the use of a composite structure: flexible body with clamps at each end. 2. The simple working principle and control of the inchworm inspired actuator makes it more accurate and precise.	

Table 18 continued

No.	Biomimetic product	Conventional product	Difference in strategies	Characteristics of biomimetic product	Characteristics of biological system
2	Moth eye inspired anti-glare displays: Surface has array of micro-structural bumps or burls smaller than the wavelength of visible light. They gently increase the refractive index between the air and medium. This decreases reflection by effectively removing the air-lens interface.	Anti-glare chemical coatings and multi-layer materials: Absorbing coatings are useful in reducing reflective and glare, but also affect the transmission of light through the screen. Multi-layer materials consist of alternating low-index and high-index materials that cut out reflection at specific wavelengths.	The biomimetic product uses a layer of micro-structural bumps in contrast to the conventional chemical coatings or multiple layers with varying refractive indexes. The light is manipulated and guided to reduce reflective glare.	1. The shape and size of the micro-structural bumps are optimized to guide and manipulate the incident light to eliminate reflection. 2. The moth eye inspired anti-glare surface uses discrete and self-similar micro-structural bumps to manipulate the incident light and eliminate reflection.	
3	Termite mound inspired Eastgate Building: The building uses a system of ducts and fans to draw the external air over an atrium (containing plants and running water streams) to maintain the internal temperature. The thermal exchange between the air and the atrium provides the heating/cooling.	Building with HVAC system: A conventional HVAC system isolates the building from the external environment. The internal temperature is controlled using a working fluid that is heated or cooled as desired.	The Eastgate complex integrates its internal environment with the external environment. In contrast conventional HVAC systems isolate the building from the external environment.	1. The Eastgate Building integrates the internal and external environments reducing the chances of system failure. 2. The concrete floors serve as an energy source (passive cooling: thermal energy exchange with air drawn from the exterior) in the termite mound inspired Eastgate Building. 3. Eastgate Building: Simpler and efficient temperature control system due to absence of another working fluid.	

Table 18 continued

No.	Biomimetic product	Conventional product	Difference in strategies	Characteristics of biomimetic product	Characteristics of biological system
4	Cricket inspired Flow sensors: Dense array of mechano-receptive hair like structures sense flow patterns.	Microphone-speaker system: A diaphragm detects flow patterns that are then translated into sound.	The biomimetic product uses discrete self-similar fibers: pneumatic energy -> mechanical energy -> acoustic energy. Traditional product uses a diaphragm.	1. The cricket inspired flow sensor's array of hair-like fibrous structures ensures sensing redundancy. 2. Shape and size of the cricket inspired flow sensor's mechano-receptive hair allows for higher sensitivities. 3. The sensory hairs deform (physically) to under the influence of external stimuli (airflow). This deformation is detected and captured by the cells.	

Table 18 continued

No.	Biomimetic product	Conventional product	Difference in strategies	Characteristics of biomimetic product	Characteristics of biological system
5	Gecko inspired adhesive tape: The tape's surface consists of nanoscale hair like structures arranged in a grid. Their interaction with the external surface causes adhesion through van der waals forces.	Adhesive Tape: Regular adhesive tapes/pads' surface has chemical glue that causes adhesion.	The biomimetic product uses discrete nanoscale hair like structures for adhesion versus the chemical coatings used by conventional products.	1. The gecko inspired tape consists of nano-scale hair like structures attached in a grid pattern on a smooth and flexible tape. 2. The nanoscale hair like structures on the gecko inspired tape facilitates adhesion as well as self-cleaning. 3. The form, shape, and arrangement of the nanoscale hair like structures on the gecko inspired tape can make the tape directional. 4. The gecko inspired tape's numerous self-similar hair-like microstructures ensure adhesion redundancy. 5. The Gecko inspired tape uses the external surface (along with its fibrous structures) to keep itself clean and re-usable.	

Table 18 continued

No.	Biomimetic product	Conventional product	Difference in strategies	Characteristics of biomimetic product	Characteristics of biological system
6	Shinkansen train's noise regulating nose: The train's nose is shaped to minimize resistance as the train speeds through the tunnels where air pressure can build to cause large sonic booms.	Noise cancellation devices:	The strategy is to optimize the product/system's shape (train's nose) to help manipulate the airflow thereby meeting the sound requirements.	1. The nose's optimized shape manipulates air flowing over it to reduce air pressure accumulation. 2. The Shinkansen train's nose prevents the development of large pressure vortices and avoids the need for noise cancellation devices.	
7	Insect inspired obstacle avoidance system: The bio-inspired navigation system uses simple qualitative representations for direction.	Robot navigation systems: Complex navigation systems use accurate directional and quantitative assessment to control direction.	The biomimetic strategy is based on simplicity in the form of two important characteristics: a wide field of view and qualitative representations (involves perceiving depth accurately).	1. Wide field of view eliminates expensive directional control system needs. 2. Qualitative representations reduces computational load on navigation system.	
8	Lotus inspired self-cleaning surfaces: Nano-scale ridged protrusions covered with hydrophobic wax make up the lotus inspired surface. This makes the surface highly hydrophobic and minimizes adhesion with any dirt particles. The water droplets therefore retain a spherical shape and carry the dirt particles of the surface as they roll-off.	Conventional surface cleaners: External chemical cleaning agents are used to clean regular surfaces. This process is not only energy intensive but also does not ensure the prevention of dirt accumulation.	The biomimetic surface's strategy involves prevention by minimizing dirt accumulation itself. Conventional cleaners are corrective measures taken after a considerable amount of dirt has been accumulated on the surface.	1. The lotus inspired self-cleaning surface is covered with discrete ridged nano-scale protrusions to prevent the accumulation of dirt particles between the ridges. 2. An important part of the lotus inspired surface's strategy is to prevent the accumulation of dirt rather than react after the dirt has been accumulated.	1. The lotus uses water flowing over it (along with its surface structure) to prevent unwanted dirt particles form adhering to its surface.

Table 18 continued

No.	Biomimetic product	Conventional product	Difference in strategies	Characteristics of biomimetic product	Characteristics of biological system
9	Velcro: The cocklebur inspired design uses two straps that can attach to each other to bond the external surfaces they are attached to. One strap has densely arrayed hooks while the other has loose fibers.	Adhesive tapes: Regular adhesive tapes/pads' surfaces have chemical glue that causes adhesion.	Velcro's uses discrete hook structures and a fibrous mating strap to achieve bonding versus the chemical coatings used by conventional products.	1. Velcro's array of discrete hooks ensures mating redundancy to a fibrous strap. 2. Velcro: The shape and size of the hooks are optimized to attach to the fibrous strap. 3. Velcro: Using a dedicated fibrous mating strap optimized to attach to the designed hooks ensures the hooks' ability to achieve their function.	1. The cocklebur plant's seeds leverage the surrounding environment (animals with fur, birds with feathers) for dispersal.
10	Speedo FastSkin Swimsuit: The sharkskin's ribbed deticles inspire the textured surface finish of the swimsuit's fabric. The textured grooves manipulate the water flow along the suit surface to reduce drag.	Conventional Swimsuits: Conventional suits enhance swimming speeds by ensuring tight body fits and lightweight.	In addition to the fit and the weight, the biomimetic swimsuit also uses surface texture to manipulate the water flowing over it to reduce drag.	1. The rough surface texture manipulates the water flowing over the suit to reduce drag.	1. The shark uses the water flowing along its surface (along with it ribbed denticles) to keep its skin clean. 2. The shark's dermal denticles (scales) reduce drag and keep the skin clean. 3. The discrete denticles (scales) on the shark's skin reduce drag. 4. The shark's dermal denticles prevent dirt particles from adhering to the skin.

Table 18 continued

No.	Biomimetic product	Conventional product	Difference in strategies	Characteristics of biomimetic product	Characteristics of biological system
11	Namibian beetle inspired water harvester: Inspired by the beetle's wings, materials with similar hydrophilic peaks and burled hydrophobic lowlands have been designed to collect water from the mist and fog. The composite structure is angled to ensure that the water flows down to a collector.		The composite material leverages the surrounding environment (fog for the water and gravity to direct the water flow) to collect water.	1. The Namibian beetle inspired material used to collect water is a composite made out of hydrophilic peaks and burled hydrophobic lowlands. 2. The water harvesting material's hydrophilic peaks attract water from the fog collecting it in droplets which then 'roll' down over a shaped hydrophobic region. 3. Owing to its shape, the beetle inspired water harvesting system leverages gravity to direct water flow and ensure energy efficient collection. 4. The water harvesting material consists of discrete hydrophilic peaks to enhance the water collection volume.	
12	Toothed windmill blades: The humpback whale's flipper inspired the toothed design of the windmill blades leading edge and periphery. These tubercles regulate the vortices generation and flow of the water. They increase efficiency and performance at low wind speeds.	Regular windmill blades: Besides not being as efficient, conventional windmill blades also do not perform well at low wind speeds.	The strategy of the new windmill blade is to use troughs and tubercles to guide and manipulate the airflow over it.	1. The blades' toothed (troughs and tubercles) leading edge design guides and manipulates the airflow over its surface. 2. The whale flipper inspired windmill blades' leading edge consists of discrete peaks and troughs (toothed edge).	

Table 18 continued

No.	Biomimetic product	Conventional product	Difference in strategies	Characteristics of biomimetic product	Characteristics of biological system
13	Owl feather inspired Shinkansen train pantograph: The train's pantograph has serrated edges (inspired by the owl's flight feathers) inscribed on the pantographs. These edges create small vortices that in turn prevent the formation of larger noisier vortices.	Noise cancellation devices:	The strategy involves optimizing the pantograph's shape to manipulate and control the airflow across it.	1. The numerous serrated edges manipulate the air flowing across the Shinkansen train pantograph to ensure lower noise levels. 2. The shape of the edges on the pantograph is optimized to create smaller vortices in the airflow that in turn help with noise regulation. 3. The Shinkansen train's owl inspired serrated pantograph design prevents the generation of large air vortices and avoids the need for noise cancellation devices.	
14	Mirasol Displays: The mirasol display is made up of numerous Interferometer Modulator (IMOD) elements. An IMOD is a simple MEMS device composed of two conductive plates. One is a thin film stack on a glass substrate and the other is a reflective membrane. Incident light therefore reflects of the thin-film stack and the reflective membrane. The gap between the two dictates the color of the reflected light. This mechanism is inspired by the butterfly's ability to adjust the form and spacing of the layers on its scales to control the wavelength of the reflected light.	Liquid Crystal Displays:	The strategy inspired by the butterfly wings involves controlling the reflection of incident light to display the required colors.	1. The dynamic IMOD element's air cavity is controlled to manipulate the wavelength (color) of the light reflected by it. 2. The butterfly wing inspired Mirasol display is made up of numerous IMOD elements arranged in a grid to generate a color picture or video.	

Table 18 continued

No.	Biomimetic product	Conventional product	Difference in strategies	Characteristics of biomimetic product	Characteristics of biological system
15	Mercedes Benz bionic concept car: The boxfish inspired car employs the optimized structural features and aerodynamic shape of the boxfish to make the car light wieght, safe, and efficeint.	Conventional car in same size category: Conventional car designs often have optimized shapes to meet aerodynamic needs. However, the boxfish inspired design is not only more aerodynamic, but also offers a larger interior and stronger structural design.	While both products attempt to meet aerodynamic efficiency by optimizing the external shape of the car, the biomimetic product through nature's design leverages years of optimization.	1. The shape of the car is optimized to reduce air drag coeeficient leading to higher efficiency. 2.	
16	Toucan's beak inspired composite: While research in adapting the toucan beak's design for engineering applications is ongoing, it is clear that the essential concept behind the material's lightweight design and high strength is the optimized internal composite structuring. The toucan beak's interior is a rigid foam structure with interconnected cancellous bone fibers. This is sandwiched between outer layers of keratin (protein that makes up fingernails and horns).		Composite materials are not confined just to nature. However, the natural composite is different in that it is optimized with respect to the structural arrangement of its constituents at a macro-level. Most conventional composites include constituents interact at the molecular level.	1. The composite (rigid foam sandwiched by keratin protein) structure gives the toucan beak its lightweight and high strength. 2. The sandwich structure of a rigid foam and keratin layers makes the toucan beak lightweight and strong.	

Table 18 continued

No.	Biomimetic product	Conventional product	Difference in strategies	Characteristics of biomimetic product	Characteristics of biological system
17	Soil engaging components: Surfaces of mouldboard ploughs and bulldozing plates have been modified based on the surface morphologies of ground beetles. Steel-45 and Ultra High Molecular Weight – Ployethylene were used to form convex bumps on the surface. The modified ploughs and plates display improved scouring properties and required less draft than conventional tools.		The modified components employ surface morphologies to minimize soil adhesion. Other natural solutions include electro-osmosis, and flexibility.	1. The ground beetle inspired rough surface morphology minimizes soil adhesion of the soil-engaging component. 2. An important part of the ground beetle's strategy is to prevent soil adhesion rather than react after the soil has already adhered to the surface. 3. The biomimetic soil engaging components' surface is covered with discrete convex bumps that reduce the affinity between the soil and the surface.	
18	Nacre inspired composite material: The inspiration gained from these efficient biological composites, has led researchers to build artificial composite using similar optimized configurations. Aluminum oxide and polymethyl methacrylate have been combined into ice-template composite structure whose toughness is 300 times greater than its constituents. The resulting hybrid-ceramic displays high fracture toughness and yield strength.		Composite materials are not confined just to nature. However, the biomimetic composite is different in that it is optimized with respect to the structural arrangement of its constituents at a macro-level. Most conventional composites include constituents interact at the molecular level.	1. The Nacre inspired composite's (Aluminum oxide and polymethyl methacrylate) internal structure gives it a toughness that is 300 times greater that that of its constituents. 2. The abalone shell inspired highly ordered layered structure of constituents (Aluminum oxide and polymethyle methacrylate) result in high fracture toughness and yield strength.	

Table 18 continued

No.	Biomimetic product	Conventional product	Difference in strategies	Characteristics of biomimetic product	Characteristics of biological system
19	Tumblebug cuticle inspired composite material: The tumblebug cuticle displays excellent mechanical properties (like lightweight, high strength, and toughness) despite the presence of many holes in the structure. A specially fabricated composite laminate with the tumblebug inspired circumcolumnar layup showed higher rupture strength than that of a similar composite with holes drilled into it.		Composite materials are not confined just to nature. However, the biomimetic composite is different in that it is optimized with respect to the structural arrangement of its constituents at a macro-level. Most conventional composites include constituents interact at the molecular level.	1. The tumblebug cuticle's internal structural arrangement and layout of fibers is the key to the increased rupture strength for composites with holes in the structure.	
20	Scarabaei cuticle inspired composite material: The natural composite comprises of chitin-fiber layers and sclerous protein matrixes. The chitin-fiber layers have different orientations with crossed and helicoidal structures at different locations. A biomimetic composite with a similar helicoidal structure (each fiber layer has almost a fixed angle with respect to the fibers in its neighboring layers) was designed and fabricated. Tests showed that fracture toughness of the biomimetic composite is markedly greater than that of the 0 degree layer composite.		Composite materials are not confined just to nature. However, the biomimetic composite is different in that it is optimized with respect to the structural arrangement of its constituents at a macro-level. Most conventional composites include constituents interact at the molecular level.	1. The scarabei cuticle is a composite structure with chitin-fibers and sclerous protein matrices. 2. The helicoidal structure of chitin-fiber layers and sclerous protein matrices provides the scarabei cuticle its high fracture toughness.	

Table 18 continued

No.	Biomimetic product	Conventional product	Difference in strategies	Characteristics of biomimetic product	Characteristics of biological system
21	Campaniform Sensilla inspired strain sensing: In many insects, the companiform sensillum is a hole in the cuticle arranged such that its shape changes in response to loads on the cuticle. A cell beneath the cuticle detects this shape change. While it is counter intuitive, tests show that inserting strain sensors in the material compromises its integrity more than when using a group on small holes to measure strain deformation. Greater strain magnification can be recorded by measuring the changes in shape of holes (in the material) in contrast to measuring the strain in the surrounding material.		Instead of using external devices or intrusive objects to attain information regarding the system's state/deformation; natural systems seen to use features that are in themselves sensitive (physically) to external stimuli.	1. The optimally located holes in the cuticle deform under external stimuli. Cells detect the deformation.	

Table 18 continued

No.	Biomimetic product	Conventional product	Difference in strategies	Characteristics of biomimetic product	Characteristics of biological system
22	Biomimetic ceramic-polymer composite: The molluscan shell is a natural high strength and toughness ceramic composite with laminated and parallel layered arrangement of aragonites (a form of calcium carbonate) embedded in a pertinacious matrix. A BN/epoxy resin composite consists of 4-millimeter thick BN sheets felted with epoxy resin and is cured under pressure in a hot press. Impact fracture toughness of the biomimetic ceramic-polymer composite is found to be markedly higher than that of monolithic ceramics. This is important because while ceramics have high hardness and high temperature resistance, they have relatively low fracture toughness due to the sensitivity to existing flaws.		Composite materials are not confined just to nature. However, the biomimetic composite is different in that it is optimized with respect to the structural arrangement of its constituents at a macro-level. Most conventional composites include constituents interact at the molecular level.	1. The biomimetic composite's increased fracture toughness is attributed to the structural arrangement and orientation of its constituents.	

Table 18 continued

No.	Biomimetic product	Conventional product	Difference in strategies	Characteristics of biomimetic product	Characteristics of biological system
23	Abscission: The method for the abscission process through which a plant separates damaged leaves/flowers from itself inspired the micro-assembly abscission design. When a damaged leaf is detected the plant slows the release of the hormone Auxin. This allows abscisic acid and ethylene to manifest and breakdown portions of the stem at the junction where the leaf is attached. Similarly, the engineering system uses a polypropylene rod melted at the tip and placed onto the micro-screw. The plastic solidifies on contact and the micro-screw can be screwed into the required position. Once the terminal torque limit is reached the screw breaks off from the polypropylene rod.		The strategy prevalent in the biological and the biomimetic system is the use of an intermediate (abscission) zone to facilitate the separation of parts.	1. Plant abscission inspired micro-assembly procedure uses an intermediate part to separate two objects (Micro-screw and propylene rod).	

SECTION II:

The identified HOT characteristics are grouped and the biomimetic design principles are subsequently formulated. These are also color-coded to determine super groups. TRIZ principles similar to biomimetic design principles are also identified as seen in Table 19 below.

Table 19: Groups of HOT characteristics abstracted into biomimetic design principles

Identified HOT Characteristics	PRINCIPLES	SUPER GROUPS	Similar TRIZ principles
1. The inchworm inspired actuator eliminates the need for transformations between non-linear and linear motion with the use of a composite structure: flexible body with clamps at each end. 2. The gecko inspired tape consists of nano-scale hair like structures attached in a grid pattern on a smooth and flexible tape. 3. The Namibian beetle inspired material used to collect water is a composite made out of hydrophilic peaks and burled hydrophobic lowlands. 4. The composite (rigid foam sandwiched by keratin protein) structure gives the toucan beak its lightweight and high strength. 5. The Nacre inspired composite's (Aluminum oxide and polymethyl methacrylate) internal structure gives it a toughness that is 300 times greater than that of its constituents. 6. The scarabei cuticle is a composite structure with chitin-fibers and sclerous protein matrices.	Composite: Make single part from two or more parts with distinct material properties and functionalities.	STRUCTURE	Composite materials: Change from uniform to composite or multiple materials
1. The shape and size of the micro-structural bumps are optimized to guide and manipulate the incident light to eliminate reflection. 2. The nose's optimized shape manipulates air flowing over it to reduce air pressure accumulation. 3. The rough surface texture manipulates the water flowing over the suit to reduce drag. 4. The blades' toothed (troughs and tubercles) leading edge design guides and manipulates the airflow over its surface. 5. The shape of the edges on the pantograph is optimized to create smaller vortices in the airflow that in turn help with noise regulation. 6. The dynamic IMOD element's air cavity is controlled to manipulate the wavelength (color) of the light reflected by it. 7. The shape of the car is optimized to reduce air drag coefficient leading to higher efficiency. 8. The ground beetle inspired rough surface morphology minimizes soil adhesion of the soil-engaging component.	Flow manipulation: Use static or dynamic features to manipulate/guide/control the material or energy *flows* across the structure to meet functional needs.	MORPHOLOGY - SHAPE OR FORM	

Table 19 continued

Identified HOT Characteristics	PRINCIPLES	SUPER GROUPS	Similar TRIZ principles
1. The moth eye inspired anti-glare surface uses discrete and self-similar micro-structural bumps to manipulate the incident light and eliminate reflection. 2. The cricket inspired flow sensor's array of hair-like fibrous structures ensures sensing redundancy. 3. The gecko inspired tape's numerous self-similar hair-like microstructures ensure adhesion redundancy. 4. The lotus inspired self-cleaning surface is covered with discrete ridged nano-scale protrusions to prevent the accumulation of dirt particles between the ridges. 5. Velcro's array of discrete hooks ensures mating redundancy to a fibrous strap. 6. The discrete denticles (scales) on the shark's skin reduce drag. 7. The water harvesting material consists of discrete hydrophilic peaks to enhance the water collection volume. 8. The whale flipper inspired windmill blades' leading edge consists of discrete peaks and troughs (toothed edge). 9. The numerous serrated edges manipulate the air flowing across the Shinkansen train pantograph to ensure lower noise levels. 10. The butterfly wing inspired Mirasol display is made up of numerous IMOD elements arranged in a grid to generate a color picture or video. 11. The biomimetic soil engaging components' surface is covered with discrete convex bumps that reduce the affinity between the soil and the surface.	Substitute discrete self-similar features in place of a single feature used to achieve a critical function.	ENVIRONMENTAL INTERACTION	Segmentation: Divide an object into independent parts; increase the degree of fragmentation or segmentation
1. The Eastgate Complex integrates the internal and external environments reducing the chances of system failure.2. The Gecko inspired tape uses the external surface (along with its fibrous structures) to keep itself clean and re-usable.3. The lotus uses water flowing over it (along with its surface structure) to prevent unwanted dirt particles form adhering to its surface.4. The cocklebur plant's seeds leverage the surrounding environment (animals with fur, birds with feathers) for dispersal.5. The shark uses the water flowing along its surface (along with it ribbed denticles) to keep its skin clean.6. Owing to its shape, the beetle inspired water harvesting system leverages gravity to direct water flow and ensure energy efficient collection.	Use materials and/or energy from the environment to help the product/system accomplish its function.	FUNCTION MANIPULATION	

Table 19 continued

Identified HOT Characteristics	PRINCIPLES	SUPER GROUPS	Similar TRIZ principles
1. The concrete floors serve as an energy source (passive cooling: thermal energy exchange with air drawn from the exterior) in the termite mound inspired Eastgate Building. 2. Velcro: Using a dedicated fibrous mating strap optimized to attach to the designed hooks ensures the hooks' ability to achieve their function.	Use static and/or dynamic structures to replicate (or substitute) the natural environment that optimizes the product/system's performance.		Dynamics: Allow or design the characteristics of an object, external environment, or process to change to be optimal or to find an optimal operating condition Local quality: Change an object's structure from uniform to non-uniform, change an external environment or external influence from uniform to non-uniform; Make each part of an object function in conditions most suitable for its operation
1. Shape and size of the cricket inspired flow sensor's mechano-receptive hair allows for higher sensitivities. 2. The form, shape, and arrangement of the nano-scale hair like structures on the gecko inspired tape can make the tape directional. 3. Velcro: The shape and size of the hooks are optimized to attach to the fibrous strap. 4. The water harvesting material's hydrophilic peaks attract water from the fog collecting it in droplets which then 'roll' down over a shaped hydrophobic region. 5. The ground beetle inspired rough surface morphology minimizes soil adhesion of the soil-engaging component.	Form: Adapt and optimize the form/shape/size of the product to meet specific functional needs.		
1. The nanoscale hair like structures on the gecko inspired tape facilitates adhesion as well as self-cleaning. 2. The sharkskin's dermal denticles (ridged scales) reduce drag by manipulating the water flow over it as well as keep the skin clean due to their structure and shape.	Multi-functionality: Make the same part perform two or more distinct functions.		Universality: Make a part or object perform multiple functions; eliminate the need for other parts

Table 19 continued

Identified HOT Characteristics	PRINCIPLES	SUPER GROUPS	Similar TRIZ principles
1. The Shinkansen train's nose prevents the development of large pressure vortices and avoids the need for noise cancellation devices. 2. An important part of the lotus inspired surface's strategy is to prevent the accumulation of dirt rather than react after the dirt has been accumulated. 3. The shark's dermal denticles prevent dirt particles from adhering to the skin. 4. The Shinkansen train's owl inspired serrated pantograph design prevents the generation of large air vortices and avoids the need for noise cancellation devices. 5. An important part of the ground beetle's strategy is to prevent soil adhesion rather than react after the soil has already adhered to the surface.	Prevention over correction: Build preventive functionality into the product/system in place of reactive or corrective functionality to help achieve an overall function.		Preliminary action: Perform, before it is needed, the required change of an object either fully or partially Beforehand cushioning: Prepare emergency means beforehand to compensate for the relatively low reliability of an object
1. Plant abscission inspired micro-assembly procedure uses an intermediate part to separate two objects (Micro-screw and propylene rod).	Use part(s) or feature(s) that is sacrificed after its functionality is achieved.		Cheap short-living objects: Replace an inexpensive object with a multiple of inexpensive objects, comprising certain qualities (such as service life, for instance)Intermediary: Use an intermediary carrier article or intermediary process. Merge one object temporarily with another (which can be easily removed)
1. The sandwich structure of a rigid foam and keratin layers makes the toucan beak lightweight and strong. 2. The abalone shell inspired highly ordered layered structure of constituents (Aluminum oxide and polymethyle methacrylate) result in a high fracture toughness and yield strength. 3. The tumblebug cuticle's internal structural arrangement and layout of fibers is the key to the increased rupture strength for composites with holes in the structure. 4. The helicoidal structure of chitin-fiber layers and sclerous protein matrices provides the scarabei cuticle its high fracture toughness.	Adapt the internal structure of a composite material to meet specific functional needs		

Table 19 continued

Identified HOT Characteristics	PRINCIPLES	SUPER GROUPS	Similar TRIZ principles
1. The sensory hairs deform (physically) to under the influence of external stimuli (airflow). This deformation is detected and captured by the cells. 2. The optimally located holes in the insect cuticle deform under external stimuli. Cells detect the deformation.	Use structural features that are physically sensitive to environmental materials and/or flows		

SECTION III:

The actual outline of the principle extraction methodology presented to the students for case study 1 is presented below.

Defined terminology

Biomimetic Product Pair: A biomimetic product pair refers to a given natural system and its corresponding bio-inspired engineering product.
Natural System: A biological system or natural system that inspires a potential engineering application or product.

The proposed principle extraction methodology integrates existing theories and methods to comprehensively analyze a given biomimetic product pair or natural system for inherent biomimetic design principles. Each step of the methodology is explained in detail below.

STEP 1: Identify bio-inspired product pair or appropriate natural system

The overall selection criterion is divided into two parts: preliminary criteria and secondary criteria. Therefore, only those products or systems that meet the first part are considered for the thorough examination in the second part.

Preliminary requirements/criteria:
Any biomimetic product pair or natural system analyzed using the developed methodology must meet the following two criterions.

1. *Innovative biomimetic product pair or natural system:*
   A biomimetic design concept or product is considered for further analysis if it is considered to be novel, new, and creative.
   A natural system is considered for further analysis if it displays sufficient potential for a specific engineering application that is novel, new, and creative.

2. *Sufficient knowledge of the biomimetic product pair (both the natural system and the bio-inspired engineering system) or natural system (both the natural system and the proposed bio-inspired engineering system) must be available to allow for a comprehensive analysis of its working.*
   Without a detailed understanding of the product or system's components and working, it is very difficult to identify characteristics that make it robust in terms of achieving its functions. This criterion is aimed at avoiding the analysis of newly proposed biomimetic products with insufficient information regarding its components, performance, and working.

Secondary requirements/criteria: Elimination
Concepts, products, or systems that fall under the following categories are not considered in this research and cannot be analyzed using the developed methodology. This is primarily because such systems/products do not lend themselves to a straightforward analysis using the theory of highly optimized tolerance, which forms a part of the subsequent methodology. All the categories of proposed biomimetic products not considered in this research are listed below.

1. *Imitating the motion of a natural system*
   Imitating motions of specific natural systems (like insect's locomotion, fish's body motion, and insect's wing motion) can be beneficial for certain engineering applications.
   However, it is difficult to analyze a type of motion in terms of its robust characteristics. Additionally, there exists a large disparity in the material properties and abilities of a biological system in comparison to a mimicking engineered system. As a result, the developed methodology cannot be used to analyze such systems for biomimetic design principles.

2. *Imitating the behavior of a biological community*
   Insect foraging and other social activities have provided inspiration in the areas of adaptive controls and robotics.
   It is difficult to analyze specific behaviors in terms of their robustness. Other considerations that are hard to quantify and relate to engineering features are the possibility of learning over time and intelligence. Additionally, inspiration in terms of individual interactions within communities is very abstract and identifying such a system's robust characteristics is not effective or reliable.

3. *Copying chemical compositions from nature*
   It is difficult to characterize a given chemical compound or composition as robust. Secondly, a chemical composition or compound cannot be classified as a complex system (at a macro level) and therefore doesn't lend itself to an analysis using the theory of highly optimized tolerance.

   It is important to note that engineering systems inspired by natural composites can be analyzed using the developed methodology and must not be eliminated. This includes constituent compounds or material put together at a macro level (as opposed to the molecular level) with specific attention paid to the structural arrangement. Examples of such biological systems include the red abalone snail's shell and the toucan's beak.

4. *Processes or methods used to manufacture a biomimetic product*
   Unlike the biomimetic product itself, processes or methods used to manufacture biomimetic products do not incorporate characteristics inspired by natural systems. As a result, analyzing them is not fruitful with respect to the eventual goal of creating a set of biomimetic design principles.

Before analyzing a specific biomimetic product pair or natural system using the developed methodology, it must be tested against all the above criteria. If it falls under any of aforementioned categories, the developed methodology would not be successful in identifying the underlying biomimetic design principles (if there are any present).

STEP 2: Determine natural system, bio-inspired engineering product, and/or conventional product

This step is performed once the biomimetic product pair or natural system (to be analyzed) has met all the required criteria. The process for each case (analyzing a biomimetic product pair and a natural system) is detailed below.

1. **Biomimetic product pair:**
   In the case of a biomimetic product pair, the biological/natural system that inspired it is identified. Second, the corresponding conventional engineering product is identified if it exists. The term conventional product used here refers to an existing product that is not bio-inspired, but accomplishes the same overall function. This is illustrated with an example below.

2. **Natural system:**
   In the case of a natural system, its prospective or proposed bio-inspired engineering product and its proposed application or overall function are identified. Next, the corresponding conventional engineering product is identified if it exists. Again, the term conventional product used here refers to an existing product that is not bio-inspired, but accomplishes the same overall function.

STEP 3: Functional modeling

Once the natural system, bio-inspired engineering product, and/or conventional product are identified, they are functionally modeled.

The functional modeling methodology (from Nagel et al) is adapted differently to model natural systems and bio-inspired engineering products. The two methods are presented in detail below.

Natural System Functional Modeling Method
The method guides a user to develop a correct, accurate, and effective functional model for a natural system.

1. Review and understand the natural system specifically in terms of its proposed bio-inspired engineering application/product
   - Understand the detailed working of the natural system specifically the aspects that inspire the proposed bio-inspired engineering product or application.

2. Define the design question solved by the proposed bio-inspired engineering product
   - Pose a design question whose solution is the proposed bio-inspired engineering system.
   - It must highlight the overall function of the product and any constraints associated with the product's design.

3. Define the category and scope of the functional model
   - Review the four biological categories:
     - Physiology: Functions and activities of a biological system
     - Morphology: Form and structure of a biological system
     - Behavior: Responses of a biological system to internal and external stimuli
     - Strategy: Common behavior exhibited by multiple biological systems to fulfill different needs.
   - Use the inspired engineering product's viewpoint to determine the category that best captures the inspiring features of the natural system.
   - This information helps scope the functional model and defines its boundaries.

4. Define the desired scale of the model
   - Compare the natural system and the proposed bio-inspired engineering system to identify the appropriate scale for the functional model.
   - The chosen scale must capture the natural system's sub-functions, features, structures, strategies, or behaviors that inspire the proposed engineering product or application.

5. Functionally model the natural system within the bounds set by the design question, biological category, and biological scale.
   - Use the engineering-to-biology thesaurus to suitably represent biological flows and functions in the functional basis terminology.
   - Use basic functional modeling guidelines to accurately model the system.

6. Check and/or validate the functional model against the design question and black box model
   - Ensure that all the function-flow pairs are represented using the functional basis terms. Use the engineering-to-biology thesaurus as a guide.
   - Ensure that the functional model captures the natural system's sub-functions, features, structures, strategies, or behaviors that inspire the proposed engineering product or application.

Bio-inspired System Functional Modeling Method
Modeling bio-inspired engineering products and conventional products does not require all the steps mentioned above. The modified approach for modeling bio-inspired engineered products and conventional products is presented below.

1. Review and understand the bio-inspired engineering product or conventional product.
   - Understand the detailed working of the product.
   - For the biomimetic product it is important to understand the sub-functions, features, structures, strategies, or behaviors of the product inspired by nature.

2. Define the design question solved by the proposed bio-inspired engineering product or conventional product
   - Pose a design question whose solution is the proposed bio-inspired engineering system.
   - It must highlight the overall function of the product and any constraints associated with the product's design.

3. Define the desired scale of the model
   - The functional model should be scaled to include the sub-functions, features, structures, strategies, or behaviors inspired by nature.

4. Functionally model the system within the bounds set by the design question, biological category, and biological scale.
   - Use basic functional modeling guidelines to accurately model the system.

5. Check and/or validate the functional model against the design question and black box model
   - Ensure that all the function-flow pairs are represented using the functional basis terms.
   - Ensure that the bio-inspired engineering product's functional model captures the sub-functions, features, structures, strategies, or behaviors inspired by nature.
   - The conventional product's functional model should be similarly scoped (in terms of functionality) to that of the natural system or bio-inspired engineering product.

Working through the functional modeling steps detailed above, results in the development of the following functional models.

Original system/product pair chosen for analysis	Functional models developed
Biomimetic product pair	• Bio-inspired engineering system model • Conventional engineering product model (if exists)
Natural system	• Natural system • Conventional engineering product model (if exists)

In step 4 and step 5, the developed functional models are *compared* and *reviewed* to infer the underlying characteristics, features, and principles transferred from the biological domain to the engineering domain.

***STEP 4*: Morphological Matrices**

The functional models are *compared* using the morphological matrix method. Each functional model is comprehensively *reviewed* within the context of the theory of highly optimized tolerance.

Comparisons using Morphological Matrices

A comparison is possible only when a conventional product with the same overall functionality as the bio-inspired engineering product or natural system exists.

Used here, the morph matrices serve a different purpose. As illustrated by Tinsley et al, morphological matrices can be used to analyze the analogies or differences between two functionally modeled systems. The format of the morphological matrix used for such an analysis is presented in the Figure 43 below.

Function-Flow Pairs			**Components**	
Natural/Biomimetic Solution	**Conventional Engineered Solution**	**Primary Functionality**	**Natural/Biomimetic Solution**	**Conventional Engineered Solution**
Natural System/Inspired Product Flow 1	Conventional Product Flow 1	Function 1	Natural/Inspired Component 1	Conventional Component 1
Natural System/Inspired Product Flow 2	Conventional Product Flow 2	Function 2	Natural/Inspired Component 2	Conventional Component 2
Natural System/Inspired Product Flow 3	Conventional Product Flow 3	Function 3	Natural/Inspired Component 3	Conventional Component 3

Continue for all functions ↓

Figure 43: Morph matrix template to be used for comparative analysis

For a biomimetic product pair, the morphological matrix is used to compare the bio-inspired engineering product with its corresponding conventional product (if it exists). Similarly, when analyzing a natural system with a potential engineering application, the natural system is compared to its corresponding conventional product if it exists.

To help with the comparison, this research defines two changes a designer must look for while analyzing the morphological matrix.

1. *Solution Approach Change*: A change in the strategy used to achieve the same function
2. *Functional Change*: An addition or deletion of functions

Each function-flow pair of the morphological matrix under analysis must be reviewed to identify whether either of the defined changes describe it. Once all the function flow pairs are reviewed, all the identified changes must be noted by *'Change type'* for use later. The next step in analyzing the products and/or system involves asking questions of the functional models using the theory of highly optimized tolerance.

<u>STEP 5</u>: Questioning the functional models using the Theory of Highly Optimized Tolerance (HOT theory)

To successfully accomplish the subsequent analysis, a thorough review and understanding of the system or product's functional model and working within its defined scope is essential. Recall, that the product or system's overall function inspiring aspects set the scope and scale for their functional model.

To ensure an effective and comprehensive review of the biomimetic product pair or natural system, the method outlines the following steps for the user.

1. Understanding the definition of a HOT characteristic.
2. Questioning the functional models to ascertain HOT characteristics from the biomimetic product pair or natural system.

The first step establishes the context within which the analysis is to be performed. This context is set up by understanding the theory of highly optimized tolerance and in turn defining the term, HOT characteristic. The theory suggests that highly interconnected, non-self similar complex systems are robust in the face of anticipated and 'designed-for' conditions; yet fragile against unexpected events. Essentially, the inherent characteristics and structure of such products make them desirably robust. With this in mind, the definition of a HOT characteristic is formulated as below.

HOT characteristics: A product or system's characteristics that make it highly optimized, robust, and tolerant to 'designed-for' environmental conditions.

The term 'designed-for' environment implies that the product or system's performance in unexpected conditions or unforeseen environmental circumstances is not to be considered during the subsequent review.

Having established the definition of a HOT characteristic, it can now be used to ask specific systems level and/or parts level questions of the product or system. The answers to these questions help identify the bio-inspired sub-functions, features, structures, strategies, and behaviors, which are then abstracted into biomimetic design principles. The questions to be asked of the product or system are listed below.

a. What features/characteristics of the product or system make it robust (as in ensures the successful accomplishment of its overall functions) in terms of functionality within the 'designed-for' environment?

b. What features/characteristics of the product or system's architecture/structure (or structure) make it robust to its 'designed-for' environment?
c. What features/characteristics of the product or system's strategy optimize its performance within the 'designed-for' environment?
d. How does the product or system ensure effectively achieving its overall objective?

Questioning Guidelines:

- As previously noted, these questions must be asked at the systems level and/or parts level and in the context of the product or system's robustness in terms of achieving its overall functionalities.
- Secondly, not all systems display features or characteristics that answer all the questions above. Therefore, a user must not expect to find features or characteristics that answer all the questions for each product.
- In the case where a biomimetic product pair is to be analyzed, the questions are asked of the bio-inspired engineering product. It is important to consciously keep in mind a comparison to the conventional product and thereby answer the questions in the context of this comparison.
- On the other hand, for a natural system under analysis, the questions are asked of the natural system itself. Again, they are answered within the context of a comparison with the conventional product.

In must be noted that in the absence of a comparative conventional product, the stated questions can still be answered and the required characteristics can be inferred. Although, the user might have to spend additional time and effort to effectively infer the requisite characteristics since a comparison usually makes them easily apparent.

STUDENT RETURNS FOLLOWING AS RESULTS:

Features, characteristics, or principles that can be or are transferred from nature to engineer

SECTION IV:

The 23 natural systems and/or biomimetic systems analyzed as part of this research are described in detail below.

1. Natural System: Termites (Macrotermes Bellicosis)

African termite mounds are complex structures with diverse working principles. However, the Eastgate Centre derives its inspiration for a particular aspect or strategy of the termite mound. It draws on the mound's use of external wind energy, its internal physiology, its physical architecture, and a regulated exchange of respiratory gases between the nest and the atmosphere.

This specific model of a termite mound's working is called the induced flow model and is often referred to as the stack effect by architects and engineers. To maintain the mound' internal environment at the desired conditions, termites constantly open and close a series of heating and cooling vents throughout the day. The external air is drawn in at the lower part of the mound into enclosures with muddy walls. This air then moves upwards through channels and exits from the chimneys at the top of the mound.

Other mechanisms besides this induced flow ventilation are possibly involved in mediating the mound's respiratory gas exchange function. Essentially, the mound ties the external environment with the colony to effectively and efficiently work together.

Engineered System: Building Architecture

Goals: sustainable construction materials, sparing use of these materials, and low energy consumption.

Most if not all buildings use HVAC systems that isolate the structure's controlled internal environment from the outdoor flow regimes. Buildings and their complex HVAC systems can tolerate varied external environmental conditions. However, a trivial failure in the system's integrity can render the building uninhabitable. These could include power failures, circuit failures, and other perturbations to the highly optimized complex system. In fact, this isolation from its environment would leave to system helpless in the event of a failure.

The corresponding analogous natural system prevents such possible system failures by including the external environment as part of its internal climate control system. Thus, it is highly tolerant to all environmental conditions and perturbations leading to disaster are greatly reduced.

The Eastgate Complex in Zimbabwe is inspired by the termite mound's induced flow model. External air is drawn in at the first floor from an open space between the two building that make up the centre. The building's mass (analogous to the termite's physiology) heats or cools the imported air depending on which is hotter, the building concrete or the air. The air is pushed vertically upwards through ducts in the floors and leaves to buildings through the chimneys at the top.

2. Natural System: Lotus

The surface of a lotus leaf like many other surfaces in nature exhibits a highly hydrophobic behavior. Hydrophobicity is a physical property of a material to repel water. The leaf's surface nanostructure and composition minimizes adhesion forces and the contact area between the water droplets and the leaf. Water droplets on such surfaces retain a spherical shape and exhibit contact angles much greater than 90 degrees.

Epidermal nano-scale protrusions called papillae form a rough surface on the lotus leaf. These ridged microstructures are covered with hydrophobic wax crystals, which prevent water from entering the narrow channels between the protrusions. Therefore, on an angled surface like that of the lotus leaf, water droplets easily roll off. Importantly, the dirt on the leaf's surface adheres to these water droplets and rolls off with it.

This self-cleaning mechanism of the lotus leaf prevents bacteria and fungi from settling on its surface.

Engineered System: Self-cleaning surfaces

Many engineering and design applications can benefit from the self-cleaning mechanism employed by the lotus leaf. Self-cleaning building paint and roof tiles have been developed using the natural lotus leaf analogy. Other applications being researched include self-cleaning solar panels, automotive windshields, and clothes.

As it is observed in many natural systems, the lotus leaf uses prevention as the optimal solution to bacterial and fungal contamination. However, engineering systems are mostly use responsive or corrective measures to meet such design requirements.

Additionally, this self-cleaning mechanism perfected by natural evolution is completely non-toxic and environment friendly. The cleaning is also achieved without the use of a separate cleaning mechanism. Contrastingly, most cleaning applications of human engineered systems use toxic and harmful detergents leading to harmful effects on the environment.

3. Natural System: Visual sensing and navigation of insects

Insects use a simple navigation system that is robust in its implementation. Their compound eyes, which are fixed with respect to the body, provide a wide field of view. These compound eyes efficiently deal with 3-D vision despite their inability to infer or perceive depth.

The simplicity inherent in the insects' visual sensing and navigation system underlines its effective robustness to external stimuli in varied environments. Unlike the complex human eye movement system, insects possess two fixed compound eyes. They make up for the lack of directional control through the wide field of view. Additionally, the inability to adjust and focus leads to a simple solid-state vision system.

The retina photoreceptors detect varying light contrasts in the visual field. Information perceived from the visual field is represented qualitatively which enables the insects to adapt appropriately. A qualitative representation indicates whether obstacles are 'close', 'moving fast', or 'looming' rather than indicating precise and complex positioning details.

Engineered System: Sensing and navigation in robots

There are varied robotic guidance and control systems with different underlying concepts. However, these complex navigation systems are not only costly but also prone to more failure as characterized by HOT.

The specific bio-inspired navigation system inherits the simplicity of the analogous insect mechanism. In contrast to complex and highly computational navigation systems, the bio-inspired design integrates the sensing and control into a single unit.

Driven by qualitative representation, immediate adaptation in the robot's path is possible without the use of specific and detailed metric driven calculations. This reduction in high accuracy affords the system to become more robust to environment changes.

4. Natural System: Gecko foot attachment mechanism

The gecko's remarkable ability to climb vertical smooth surfaces has been attributed to molecular van der Waal's forces. Each gecko foot consists of an array of setae arranged in a grid-like pattern. Each setae tip consists of a nano-scale array of hundreds of spatular tips. The size and shape of the tips result in the adhesion.

This simple mechanism is robust to surface type, chemistry, wetness, and other environmental conditions. Additionally, the gecko can activate and deactivate the adhesion by dragging its foot along the surface and pealing it off the surface respectively.

Engineered System: Synthetic dry adhesives

Dry adhesives inspired by the gecko foot's hair-like structures have varied possible applications in robotics and fastening. Experimental research has led to the development of numerous different adhesive pads and tapes using different manufacturing techniques. Despite different methods and technologies the basic criteria includes using numerous nano-scale hair-like structures arranged in a grid like pattern.

Unlike current adhesive tapes, the gecko inspired tape is reusable. Other robust properties include its directionality and dry attachment characteristics.

5. Natural System: Flow-sensors used by Crickets

Crickets use mechano-receptive hairs situated on two protruding body appendices called cerci. The flow-sensitive hair and mechanical filtering allow the cricket to perceive signals near the noise limits.

Most engineered acoustic sensors use pressure sensing, but the flow sensing ability of the cricket allows it to perceive even at noise limits including thermal noise. This mechanism is adapted to allow the cricket to sense the presence of predators. Predators like wasps are too small to produce significant pressure variations, but there proximity can allow the cricket to sense particle flows resulting from the predator's movement.

Adapted to meet specific requirements, the cricket's hairs are highly sensitive and therefore robust to the designed for conditions. The airflow causes the hair to tilt and in turn apply pressure to neurons in the base socket. This effect is greatly enhanced by the mechanical lever amplification principle. Therefore a cricket can sense movements of small and lightweight predators at close distances.

Engineered System: Engineered flow-sensors

Engineered pressure based sensors cannot perceive sound at the noise limits. Biomimetic designs based on the cricket's mechano-sensing mechanism have been developed. Although, current designs are not as efficient and effective as the biological counterpart, they do show great promise.

Current acoustic sensing systems perform filtering and amplification using electrical circuits and are therefore have a limited sensing range. Flow sensing allows for a greater sensing range due to the absence of circuit disturbances. Additionally, arranging the flow sensors in a densely packed array allows the system to perceive flow patterns rather than measurements at a single point.

6. Natural System: Inchworm motion

The inchworm is the larvae of the Geometridae family of moths. Inchworms exhibit a peculiar method of locomotion using three pairs of fore legs and two pairs of rear legs attached to its slender flexible body. The worm grips the ground with its front legs while drawing the hind end forward, which is followed by griping with its rear legs and advancing its front end.

Such motion is inherently simple, stable, and highly accurate. Such stability aids the inchworms defenses against predators. Under threat, the inchworm often stands upright on its fore legs resembling a twig or thorn on the tree.

Engineered System: Inchworm linear motors/actuators

Engineers have developed actuators and motors inspired by the motion of the inchworm. The natural motion’s highly optimized characteristics such as simplicity, stability, and accuracy make it ideal for many industrial applications.

The engineered inchworm systems have varied configurations, but all the designs are based on using two clamps/brakes and a flexible body. The clamps are connected by the flexible body and are housed on a shaft or within guide rails. Electrical signals direct the breaking and releasing mechanism for the front and rear clamps. Thus, the inchworm inspired motor or actuator moves a single step at a time.

Engineered inchworm systems can produces forces of over 30N while maintaining accuracy and stability. Thus, they are highly optimized to meet applications that require accurate griping or motion.

7. Natural System: Cocklebur plant seed dispersal

The spherical seeds or burs of the cocklebur are covered with small hooks that can attach to animal fur, feathers, and any other fibrous material. Owing to the spherical shape and the densely arrayed hooks on its surface, the burs efficiently disperse the cocklebur seeds using animals and birds for transport.

Therefore, the bur's design is robust to its designed for environment. These characteristics include its lightweight, omni-directional attachment, and hook redundancy.

Engineered System: Velcro® fastener

Inspired by the cocklebur design, the Velcro fastener consists of a strap with densely arrayed hooks and a complementary strap with loose fibers. The hooks attach to the loose fibers allowing the two straps to mate while pulling them apart releases the fiber-hook bond.

Unlike, the bur design engineering fastening applications do not necessarily require omni-directionality and therefore specific Velcro straps can be designed for specific applications. This optimized characteristic shape increases the design's robustness to the specific design condition. Additionally, the hook and fiber densities are varied to match the bond strength of the design requirements. The strap with the loose fibers is specifically design to match the hook strap thereby providing an optimized environment for the hooks.

8. Natural System: Shark's skin

Ribbed scales called dermal denticles cover the shark's skin. These ridges reduce water turbulence at the skin surface. As a result, the water flows past the shark's skin at a greater speed.

The shape, size, and alignment of the ribbed denticles have been optimized through evolution to provide a robust mechanism that allows the shark to swim efficiently at high speeds. These ribbed grooves accelerate the water flowing near the skin surface (since a fixed volume of water going through a narrower channel flows faster) thereby reducing the disparity between the speed of the water flowing at the skin surface and that flowing farther away from the skin. They also channel the water over the sharkskin's surface to ensure that any turbulence created results in smaller vortices. Shape, size, and alignment of denticles vary along the skin so as to effectively aid streamline forward motion.

The rough texture repels unwanted microbes that otherwise adhere to the skin free surface area. The denticles' grooves accelerate the water flowing through them, thereby washing away fouling organisms that manage to adhere to the skin.

Engineered System: Speedo FastSkin® swimsuit

The Speedo FastSkin body suit uses different textured fabrics along the body contour. Like the shark's dermal dentices the swimsuit's texture reduces turbulence and drag.

The optimal denticle arrangement of the shark's skin is used as a template to provide different textures at different location on the suit. This optimized texturing takes into account the swimmers body shape and swimming style. For instance, sharks possess bigger and more pronounced denticles along the front end of its body. Similarly, the Speedo suit uses extra roughness along the chest and back area of the body.

Other important optimized characteristics like suit weight and elastic fit also increase the design's robustness.

9. Natural System: Moth's eyes

The eye's surface consists of an array of micro-structural bumps or burls. These microstructures interfere with the reflection and transmition of light. This increases the refractive index of the surface.

The evolved and optimized designed allows the moth's eyes to collect as much light as possible without reflection. Preventing reflection is key to avoid being detected by predators during the night. In fact, the spherical shape of the eyes ensures that the reflection is prevented even at high angles of incidence.

Engineered System: Solar panels, flat panel displays, touch screen interfaces etc

Engineering applications that require highly optimized anti-reflection and anti-glare characteristics can take inspiration from the moth's eyes. Films and coatings inspired by the eye structure can help increase efficiency of solar panels by reducing light ray reflection. They can also help improve anti-reflective surfaces.

Optimized microstructure array specifications like shape and size can effectively increase the specific designs robustness.

10. Natural System: Namibian beetle's water harvesting mechanism

The wing surface of the Namibian beetle consists of hydrophilic protruding peaks and hydrophobic burled lowland. This composite structure allows the beetle to harvest water from water vapor mists. The wing surface is angled to ensure that the water collected flows to the beetle's mouth.

The hydrophilic peaks attract water droplets from the fog. These condensed droplets then flow down along the hydrophobic lowland (which prevent water loss) to the beetle's mouth.

The peaks are optimally arrayed along the curved and angled wing surface to ensure maximum water harvesting while ensuring enough surface area for the water droplets to flow towards the mouth. This is important to the beetle's survival in the desert.

Engineered System: Water harvesting material

Materials with similar hydrophilic peaks and burled hydrophobic lowland have been designed to collect water from the mist and fog. Their orientation, size, shape, and structure are optimized based on the application and its location.

11. Natural System: Whale flipper

Whales are large and heavy creatures, but display desirable maneuverability and speed while swimming underwater. In fact, the whale's flippers generate incredible force while traversing tightly banked corners. Studies have found that a combination of troughs along the leading edge and tubercles or edged nodules along the periphery allow the flippers to create the required forces.

The troughs create large vortices while the tubercles form straight streamline flow patterns that delay stalling. Stalling is detrimental to effectively maneuvering tight turns at high speeds. However, the optimized flipper design works robustly within its designed-for environment.

Engineered System: Windmill blades, fans, wings etc

The whale's ability to efficiently maneuver tight turns is attributed to its flipper design. This has inspired its application to other engineering problems such as improving windmill blade design to increase efficiency.

The toothed blades are optimized to improve the blades' aerodynamics. Other applications include increasing the efficiency of fans, submarines, and airplane wings.

12. Natural System: Mother-of-Pearl (or Nacre)

The red abalone snail's nacre shell is highly robust to its environmental requirements. It is a composite structure made out of calcium carbonate and an adhesive protein called Lustrin A. Calcium carbonate is an inherently brittle material, but the composite shell is 30000 times more resistant to fracture.

The composition consists of 95% calcium carbonate (in a aragonite crystal form) and 5% soft protein in a highly ordered layer structure. The remarkable structural and mechanical characteristics of the shell are a result of the highly optimized internal organization and structure.

The adhesive protein is strong enough to hold the aragonite crystals together, while also weak enough to allow the layers to slide so as to absorb the energy from a physical impact. Additionally, the snail repairs the damaged areas within the shell and also uses self-repairing deposits at interfaces.

It is important to note that many other composite materials in nature use highly optimized internal structures resulting in remarkable properties. These include tough biological composite materials like mollusk shells, bird bills, deer antler, and animal tendons among others.

Engineered System: Lightweight composite Materials

The inspiration gained from these efficient biological composites, has led researchers to build artificial composite using similar optimized configurations. Aluminm oxide and polymethyl methacrylate have been combined into ice-templated composite structure whose toughness is 300 times greater than its constituents. The resulting hybrid-ceramic displays high fracture toughness and yield strength.

Like the abalone shell, optimized internal structuring can result in controlling a composite's directional physical properties. Therefore, from nature we learn that the key is in the arrangement and internal structuring rather than the composite materials used. This is a shift in the established engineering paradigm.

13. Natural System: Owl flight feathers

Research has revealed that an owl's flight feathers are unlike most birds. Most birds have wings lined with feathers that have a sharp clean edge. Contrastingly, owls have many saw-toothed feathers protruding from the outer rim of their primary feathers.

These saw-toothed tips generate small vortexes in the airflow, thus breaking up the larger noise producing vortexes. The owl relies on its silent and stealthy features to catch its prey and survive.

Engineered System: 500-series Shinkansen bullet train and Stealth aircraft

The Shinkansen bullet train is one of the fastest trains ever built. However, its high speed also results in creating loud and disturbing noise. To reduce this noise, the train's engineers took inspiration from the owl's feathers.

The train uses serrated edges inscribed on the main pantograph (which transfers electricity from overhead wires to the train) to reduce the noise. The edges succeed in creating small vortexes, which in turn prevent the formation of larger noisier vortexes.

Similarly, optimized rounded edges or 'vortex generators' have been incorporated into aircrafts including stealth fighters.

14. Natural System: Kingfisher beak

The kingfisher is able to dive from a low-resistance medium, air into a high-resistance medium, water with minimal resistance and energy losses. Its ability to do the same is attributed to the beak's unique design.

The sharp cone like optimized design, allows the kingfisher to efficiently overcome the change in resistance without loosing much of its speed. This is key to the kingfisher's survival as it preys on fish.

Engineered System: 500-series Shinkansen bullet train

Owing to its high speed, the Shinkansen bullet train generates a sonic boom caused by the sudden pressure release when exiting a tunnel. Inspired by the design of the kingfisher's beak, engineers redesigned the train's nose.

The new biomimetic design, allows the train to travel through narrow tunnels without causing a sonic boon at the exit. The highly optimized nose design regulates pressure accumulation as the train travels through a tunnel.

15. Natural System: Butterfly wings

Pigmentation is the prominent method used to display color. However, the butterfly uses miniscule, transparent structures layered on its wings to display its vibrant colors. The microstructures reflect particular selective wavelengths, which in turn results in displaying certain colors.

The wavelengths reflected or colors displayed is determined by the form and spacing of the layers on the butterfly's scales. Thus the butterfly can control its coloration for camouflage, communication, and thermal regulation. Optimum structure forms can be changed based on the environmental requirements.

Engineered System: Mirasol™ displays and Morphotex fibers

The selective reflection technique used by the butterfly has inspired research in many possible engineering applications. One such application involves color display screens using the mirasol™ technology. The display uses an interferometric modulator [IMOD] element and a two-plate conductive system to display desired colors.

An IMOD element is a MEMS device that consists of two conductive plates: one a thin film stack and the other a reflective membrane. Therefore, light is reflected from the IMOD element by the thin film stack as well as the reflective membrane. These phase difference between the light reflected off the membrane and that reflecting off the thin film stack determines the color of the light reflected off the IMOD element. This is because some wavelengths constructively interfere while others destructively interfere. The phase difference is controlled by the gap between the think film stack and the membrane. Small voltages applied to the thin-film stack control the gap between the two plates. A full-color display is assembled by spatially ordering IMOD elements reflecting in the red, green and blue wavelengths.

This design saves significant energy compared to other display systems. It also offers easy visibility even in bright sunlight just like that of butterfly wings. The ideal environment for such a system is the cell phone and other handheld display systems.

Another application of the butterfly wing display design is seen in Morphotex structural fibers. These bio-inspired fibers are laminated using nanotechnology and the variations in laminate thickness and form creates different colors.

The fibers can be designed for uses in clothing fabric, powder, and paint. Importantly, this technology doesn't use dyes leading to lower energy consumption and industrial waste.

16. Natural System: Soil-adhesion in burrowing animals

Soil adhering to the skin can reduce the efficiency of burrowing animals by increasing work resistance and elevating energy consumption. However, soil-burrowing animals display remarkably effective anti-adhesion characteristics. These design characteristics that prevent soil adhesion include non-smooth surfaces structure, chemical compositions, hydrophobic properties, electro-osmosis, flexible features, and fluid lubrication. These characteristics are optimized differently for different animals based on their immediate environment and burrowing needs.

The dung beetle's surface morphology, shape, and chemical composition prevent the adhesion of soil to their bodies. Their skin's surface consists of concave hollows and convex bumps. These microstructures reduce the contact area, increase the pressure, and break down the continuity of the water film at the soil-tool interface.

A common feature of all the design characteristics (in different animals) includes preventing soil-adhesion rather than cleaning after the fact.

Engineered System: Biomimetic soil engaging components

Most conventional soil engaging equipment face problems like reduced performance efficiencies due to soil adhesion. This leads to lower work quality, work resistance, higher energy consumption, and a drop in efficiency.

Preventing soil adhesion is a desired solution and has been attempted through bio-inspiration. New designs use biomimetic characteristics like rough surfaces, electro-osmosis, and flexibility.

Surfaces of mouldboard ploughs and bulldozing plates have been modified based on the surface morphologies of ground beetles. Steel-45 and Ultra High Molecular Weight – Ployethylene were used to form convex bumps on the surface. The modified ploughs and plates display improved scouring properties and required less draft than conventional tools.

Each of these characteristics can be optimized based on the component's usage and environment of operation. Prevention is always better that correction.

17. Natural System: Boxfish

The boxfish's shape differs considerably from the appearance of fast swimmers like sharks. However, this unique structure is highly streamlined and makes the box fish very agile, stable, and an efficient swimmer. This structure is adapted to the fish's coral reef and tropical sea environment that demands a tough structure to withstand high pressures and collisions while maneuvering in tight spaces.

The angular body shape consists of bony hexagonal interlinked plates that form a rigid structure. This construction makes the structure lightweight and tough. Small vortices form along the upper and lower parts of the body thereby stabilizing the fish to ensure precise maneuverability even in turbulent waters. Thus, the boxfish's structure is rigid yet aerodynamic allowing it great agility and stability.

Engineered System: Mercedes Benz bionic concept car

Air resistance contributes considerably to a car's performance and efficiency. Inspired by the boxfish, the Mercedes Benz bionic concept car has a greatly reduced drag coefficient of just 0.19 making it most aerodynamic in its size category.

In fact, the fish's structure also inspired the lightweight construction used in the car. Computer simulations were used to optimize the body and suspension components such that the material in areas subjected to lower loads is lighter, while highly stressed areas are subject to greater reinforcement. This made the car desirably lightweight, safe, and durable.

18. Natural System: Toucan's beak

The toucan's beak is optimized for high strength, high impact resistance, and lightweight. The secret lies in the unique bio-composite structure of the beak. The beak's interior is a rigid foam structure with interconnected cancellous bone fibers. This is sandwiched between outer layers of keratin (protein that makes up fingernails and horns).

As an optimized composite structure the beak is very light in weight but very strong and resistant to impacts.

Engineered System: Toucan beak inspired composites

While research in adapting the toucan beak's design for engineering applications is ongoing, it is clear that the essential concept behind the material's lightweight design and high strength is the optimized internal composite structuring.

The applications include automotive panels that could protect passengers in crashes and ultra-light aircraft components.

19. Natural System: Circumcolumnar microstructure of Tumblebug cuticle

The tumblebug cuticle is a natural composite that displays excellent mechanical properties (like lightweight, high strength, and toughness) despite the presence of many holes in the structure. The holes are used to transport materials or receive external information.

Its properties are attributed to the laminated structure that consists of highly oriented chitin fibers and sclerotized protein matrixes. The fibers near the holes pass continuously around the holes forming a kind of circumcolumnar layup. This sustains the stress concentration around the holes and increases the strength of the natural composite.

Therefore, a detailed heterogeneous structure gives the composite its high rupture strength.

Engineered System: Biomimetic composite structure

A specially fabricated composite laminate with the circumcolumnar layup displayed higher rupture strength than that of a similar composite with holes drilled into it. Although this is a trivial result, the experiment found a greater difference in rupture strength with larger holes.

Essentially, the arrangement and layout of the fibers is the key to the increased rupture strength for composites with holes in the structure.

20. Natural System: Helicoidal microstructure of Scarabaei cuticle

The Scarabaei cuticle is a natural composite that displays excellent mechanical properties like lightweight, high strength, and toughness. The natural composite comprises of chitin-fiber layers and sclerous protein matrixes. The chitin-fiber layers have different orientations with crossed and helicoidal structures at different locations.

Engineered System: Biomimetic composite structure

A biomimetic composite with a similar helicoidal structure was designed and fabricated. In the helicoidal structure, each fiber layer has almost a fixed angle with respect to the fibers in its neighboring layers.

Comparative tests showed that the fracture toughness of the biomimetic composite is markedly greater than that of the 0 degree layer composite.

21. Natural System: Campaniform Sensilla: Measuring Strain from the Deformation of Holes

In many insects, the companiform sensillum is a hole in the cuticle arranged such that its shape changes in response to loads on the cuticle. This shape change is rotated through 90 degrees by the suspension of a bell-shaped cap whose deflection is detected by a cell beneath the cuticle.

The cuticle's superior sensitivity is attributed to the arrangement of several holes in a regular pattern.

Engineered System: Biomimetic strain sensing

Greater strain magnification can be recorded by measuring the changes in shape of such holes (in the material) in contrast to measuring the strain in the surrounding material. However, conventional methods attempt to measure the strain over the region of the deforming material.

While it is counter intuitive, inserting strain sensors in the material compromises its integrity more than when using a group on small holes to measure strain deformation. In a group of holes the dangerous stress concentrations are fewer than might be expected.

The arrangement of the holes and their shape (for directional strain measurements) can enhance sensitivities.

22. Natural System: Molluscan or bivala shell

The molluscan shell is a natural ceramic composite with excellent fracture strength and fracture toughness. This is attributed to their laminated and layered arrangement of constituent materials. Each layer consists of laminated aragonites (a form of calcium carbonate) embedded in a proteinaceous matrix and lays parallel to the surface of the shell.

The laminated aragonites are arranged in various forms that include parallel, crossed, and inclined forms. The size, shape, and arrangement adopted depend strongly on the state of the local stresses.

Engineered System: Biomimetic ceramic-polymer composite

Biomimetic ceramics based on the unique laminated microstructure observed in the molluscan shell have been designed and fabricated. An example is the BN/epoxy resin composite. Four-millimeter thick BN sheets are felted with epoxy resin, after which the laminate is cured under pressure in a hot press.

Impact fracture toughness of the biomimetic ceramic-polymer composite is found to be markedly higher than that of monolithic ceramics. This is important because while ceramics have high hardness and high temperature resistance, they have relatively low fracture toughness due to the sensitivity to existing flaws.

The key to the biomimetic composite's increased fracture toughness is the structural arrangement and orientation of its constituents.

23. Natural System: Plant abscission

Abscission is a process plants use to separate and discard the damaged or infected leaves and/or flowers. This avoids the infection from spreading to other parts of the plant. When a damaged part is detected, the plant slows the release of the hormone called Auxin. This allows abscisic acid and ethylene to manifest and breakdown the portions of the stem at the junction where the damaged part is attached.

Engineered System: Micro-assembly abscission

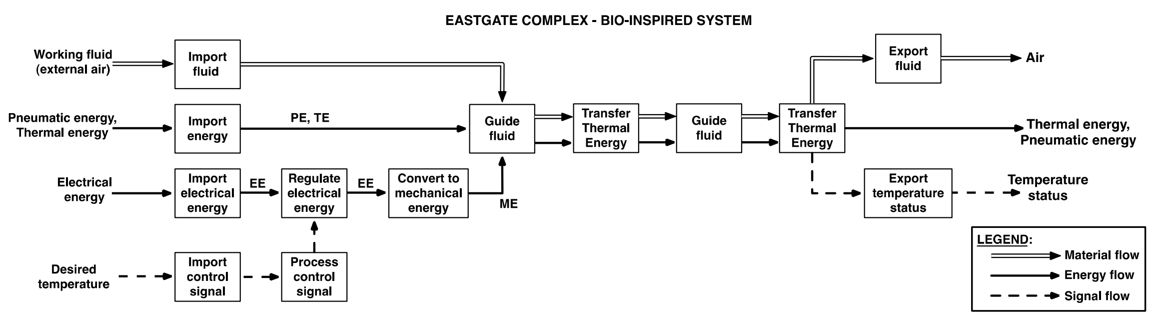
A similar strategy or method has been adapted for a micro-assembly process. A polypropylene rod is melted at the tip and placed onto a micro-screw. The melted plastic solidifies on contact and the micro-screw can be screwed into place. Once the terminal torque limit is reached the screw breaks off from the polypropylene rod.

SECTION V:

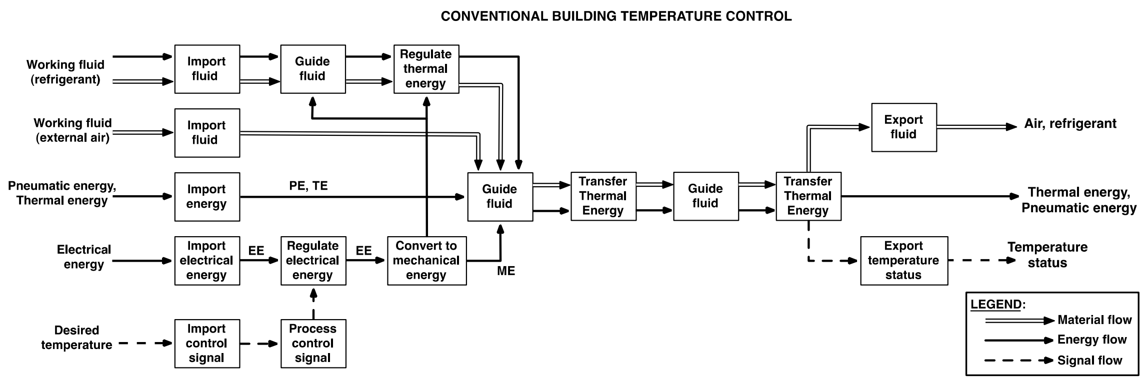
Twenty-three natural systems and/or biomimetic systems were analyzed as part of this research. For each system or product pair this subsection shows the following: the natural system's or bio-inspired product's functional model, the conventional product's functional model (if it exists), the Solution Approach Change identified from the morph matrix, and the Functional Change identified from the morph matrix. The **Solution Approach Changes** are highlighted in **blue** and the **Functional Changes** are highlighted in **red**. Additionally, a Functional Change is readily identified by a empty cells (marked with an 'X') in a morph matrix.

1. Termite's mound (Macrotermes Bellicosis) and Eastgate Complex

Bio-inspired system: Eastgate Complex functional model



Conventional system: Conventional building HVAC system functional model

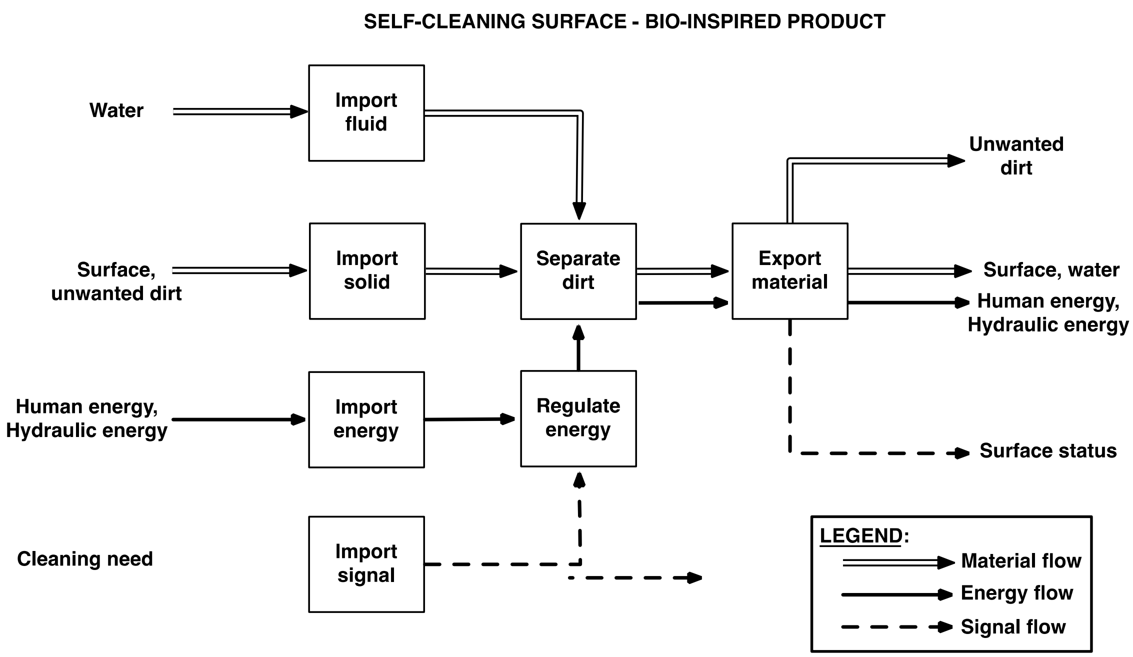


Morph matrix

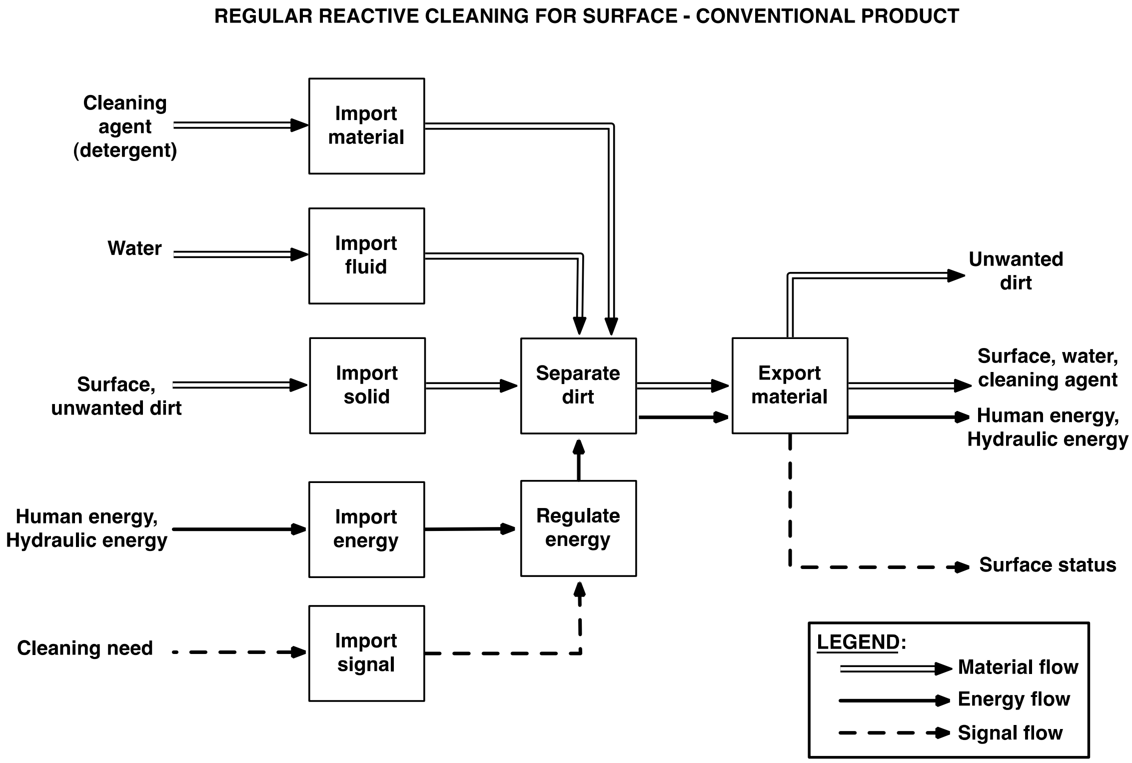
Function-Flow Pairs		**Primary Functionality**	**Components**	
Natural/Biomimetic Solution	**Conventional Engineered Solution**		**Natural/Biomimetic Solution**	**Conventional Engineered Solution**
Import fluid (external air)	Import fluid (external air)	Import	Ducts and fans	Ducts and fans
Import pneumatic and thermal energy	Import pneumatic and thermal energy (air and refrigerant)	Import	Ducts and fans	Ducts and fans
X	Import fluid (refrigerant)	Import	X	Ducts and pumps
X	Guide fluid (refrigerant)	Guide	X	Ducts and pumps
X	Regulate thermal energy (of refrigerant)	Regulate	X	Heater/Cooler
Import electrical energy	Import electrical energy	Import	Power output	Power output
Regulate electrical energy	Regulate electrical energy	Regulate	Circuit board	Circuit board
Convert electrical to mechanical energy	Convert electrical to mechanical energy	Convert	Motors	Motors, pumps
Import control signal	Import control signal	Import	Circuit board	Circuit board
Process control signal	Process control signal	Process	Circuit board	Circuit board
Guide fluid	Guide fluid (air)	Guide	Ducts and fans	Ducts and fans
Transfer thermal energy (external air temperature regulation)	Transfer thermal energy (refrigerant to external air)	Transfer	ATRIUM: Convection transfer between external air and atrium	Convection transfer between refrigerant and external air
Guide fluid	Guide fluid	Guide	Ducts	Ducts and fans
Transfer thermal energy (internal temperature regulation)	Transfer thermal energy (internal temperature regulation)	Transfer	Convection transfer between air and inhabitants	Convection transfer between air and inhabitants
Export fluid	Export fluid	Export	Ducts	Ducts and fans
Export temperature status	Export temperature status	Export	Temperature display and circuit board	Temperature display and circuit board

2. Lotus leaf and bio-inspired self-cleaning surfaces

Bio-inspired system: Self-cleaning surfaces functional model



Conventional system: Functional model of regular surfaces that use reactive cleaning methods

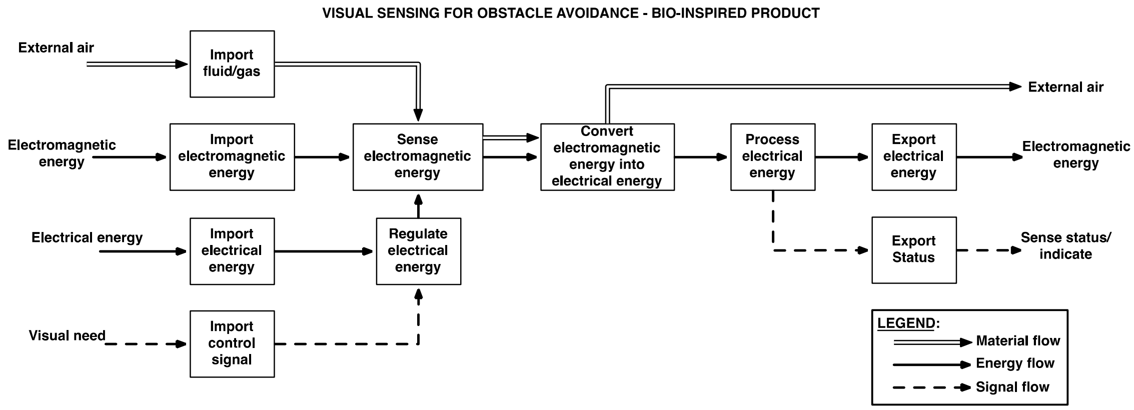


Morph matrix

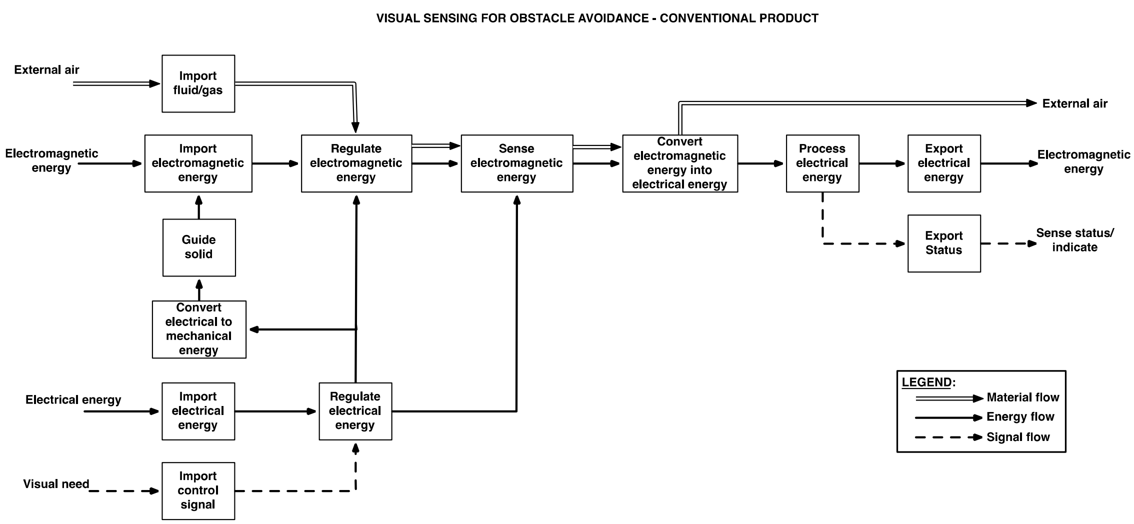
Function-Flow Pairs		Primary Functionality	Components	
Natural/Biomimetic Solution	Conventional Engineered Solution		Natural/Biomimetic Solution	Conventional Engineered Solution
Import fluid (water)	Import fluid (Water)	Import	Hand, Water source	Hand, Water source
X	Import material (cleaning agent)	Import	X	Cleaning agent (detergent)
Import solid (dirt particles)	Import solid (dirt particles)	Import	Surface	Surface
Import energy (human, hydraulic)	Import energy (human, hydraulic)	Import	Hand	Hand
Regulate energy	Regulate energy	Regulate	Hand	Hand
Import signal	Import signal	Import	Brain	Brain
Separate dirt	Separate dirt	Separate	Surface microstructure prevents dirt accumulation, water	Surface, water, cleaning agent
Export material	Export material	Export	Dirt, water, hand	Dirt, water, hand, cleaning agent

3. Visual sensing, navigation of insects and bio-inspired obstacle avoidance system

Bio-inspired system: Bio-inspired obstacle avoidance system functional model



Conventional system: Conventional robot navigation system functional model

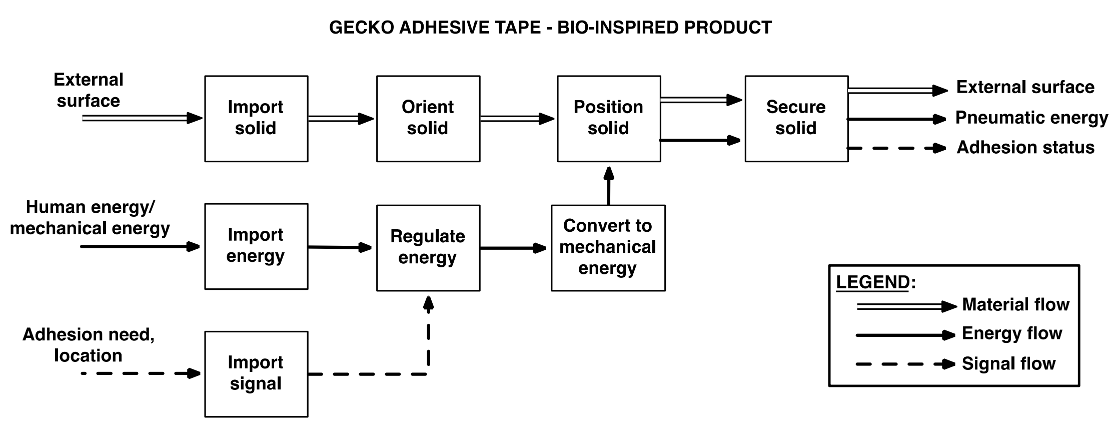


Morph matrix

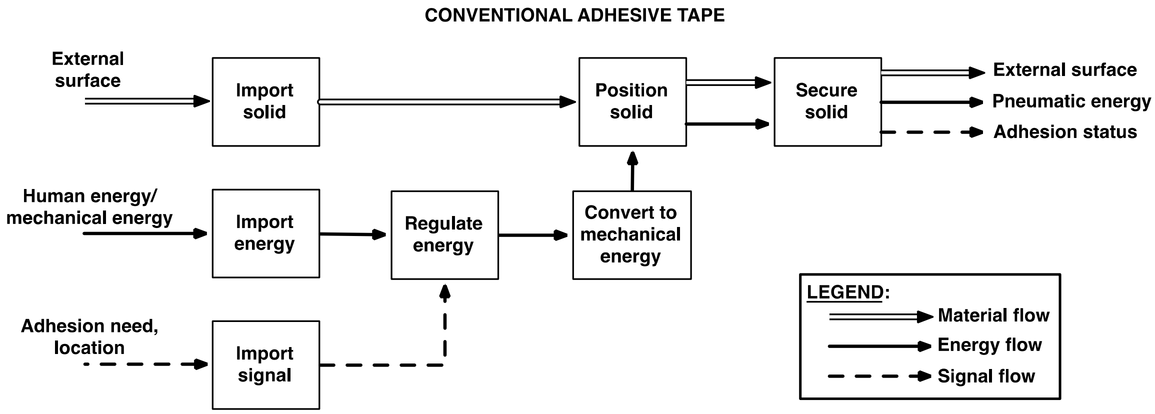
Function-Flow Pairs			Components	
Natural/Biomimetic Solution	**Conventional Engineered Solution**	**Primary Functionality**	**Natural/Biomimetic Solution**	**Conventional Engineered Solution**
Import fluid/gas	Import fluid/gas	Import	Housing	Housing
Import electromagnetic energy	Import electromagnetic energy	Import	Wide-angle Lens	Adjustable lens
X	Regulate electromagnetic energy	Regulate	X	Focusing device
Sense electromagnetic energy	Sense electromagnetic energy	Sense	Charge coupled device (CCD) or Complementary metal oxide semiconductor (CMOS)	Charge coupled device (CCD) or Complementary metal oxide semiconductor (CMOS)
Import electrical energy	Import electrical energy	Import	Circuit board	Circuit board
Regulate electrical energy	Regulate electrical energy	Regulate	Circuit board	Circuit board
X	Convert electrical to mechanical energy	Convert	X	Actuator/motor
X	Guide solid (lens housing)	Guide	X	Lens actuator/motor
Import control signal	Import control signal	Import	Circuit board	Circuit board
Convert electromagnetic to electrical energy	Convert electromagnetic to electrical energy	Convert	CCD or CMOS	CCD or CMOS
Process electrical energy	Process electrical energy	Process	Circuit board	Circuit board
Export electrical energy	Export electrical energy	Export	Circuit board	Circuit board
Export status	Export status	Export	Circuit board	Circuit board

4. Gecko foot attachment mechanism and the gecko inspired tape

Bio-inspired system: Gecko inspired tape functional model



Conventional system: Adhesive tape functional model

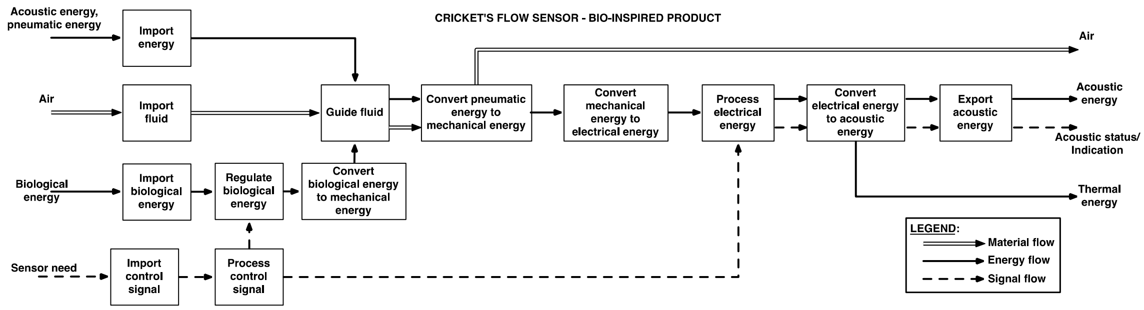


Morph matrix

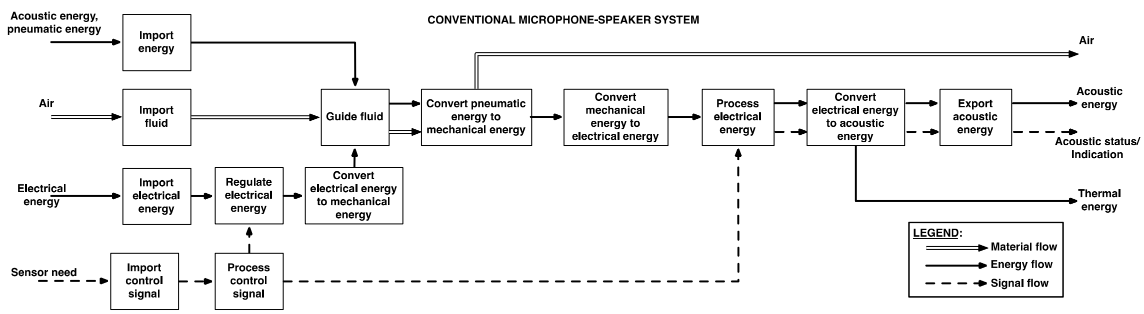
Function-Flow Pairs		Primary Functionality	Components	
Natural/Biomimetic Solution	**Conventional Engineered Solution**		**Natural/Biomimetic Solution**	**Conventional Engineered Solution**
Import solid (external surface)	Import solid (external surface)	Import	Hand/robotic arm	Hand/arm
Orient solid (with respect to tape's nanostructures)	X	Orient	Hand/robotic arm and nanostructure fiber's direction	X
Import human/mechanical energy	Import human/mechanical energy	Import	Hand/robotic arm	Hand/arm
Regulate energy	Regulate energy	Regulate	Hand/robotic arm	Hand/arm
Convert to mechanical energy	Convert to mechanical energy	Convert	Hand/robotic arm	Hand/arm
Import signal	Import signal	Import	Brain/circuit board	Brain/circuit board
Position solid	Position solid	Position	Hand/ robotic arm	Hand/arm
Secure solid	Secure solid	Secure	Nano-scale fibers	Chemical coating

5. Cricket's flow-sensors and bio-inspired flow sensor

Bio-inspired system: Cricket's flow sensor functional model



Conventional system: Microphone and speaker system functional model

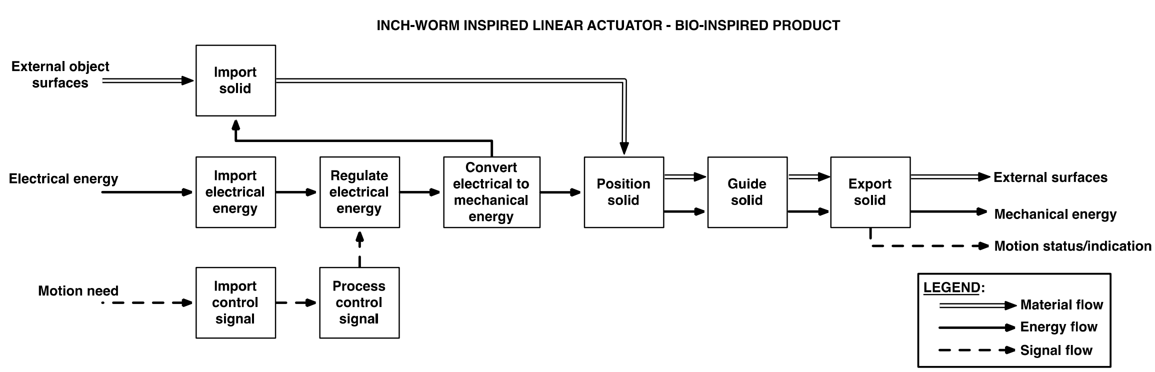


Morph matrix

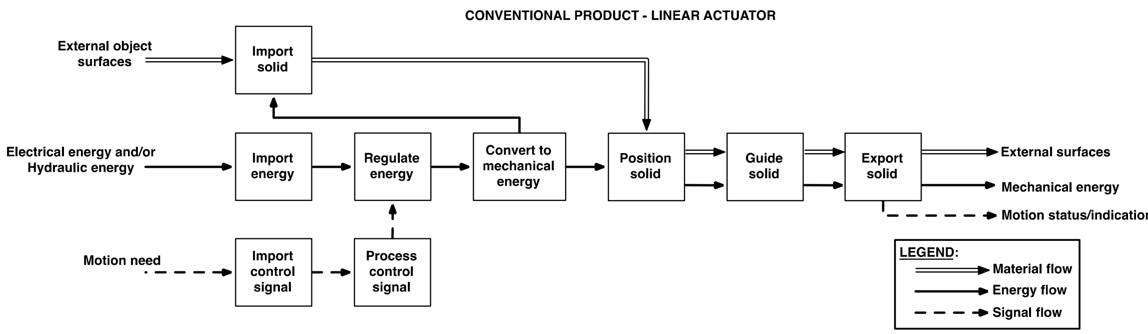
Function-Flow Pairs			Components	
Natural/Biomimetic Solution	**Conventional Engineered Solution**	**Primary Functionality**	**Natural/Biomimetic Solution**	**Conventional Engineered Solution**
Import acoustic and pneumatic energy	Import acoustic and pneumatic energy	Import	Sensor housing	Sensor housing
Import fluid (air)	Import fluid (air)	Import	Sensor housing	Sensor housing
Import biological energy	Import electrical energy	Import	Brain, cells	Battery
Regulate biological energy	Regulate electrical energy	Regulate	Cells, nerves	Circuit board
Convert biological to mechanical energy	Convert electrical energy to mechanical energy	Convert	Muscles	Actuators
Import control signal	Import control signal	Import	Brain	Circuit board
Process control signal	Process control signal	Process	Brain	Circuit board
Guide fluid	Guide fluid	Guide	Cerci - sensory arm surface	Actuators, Sensor housing
Convert pneumatic to mechanical energy	Convert pneumatic to mechanical energy	Convert	Flow sensitive Mechano-receptive hairs (SU-8 for bio-inspired product)	Pressure sensitive Diaphragm-coil-magnet setup
Convert mechanical to electrical energy	Convert mechanical to electrical energy	Convert	Hair socket and neural network (Bio-inspired product: Capacitive read-out detects hair movement using 2 electrodes on a membrane that is attached to the base of the hair)	Coil movement in magnetic field
Process electrical energy	Process electrical energy	Process	Circuit board	Circuit board
Convert electrical to acoustic energy	Convert electrical to acoustic energy	Convert	Speaker	Speaker
Export acoustic energy	Export acoustic energy	Export	Speaker housing	Speaker housing

6. Inchworm motion and bio-inspired linear actuator

Bio-inspired system: Inchworm inspired linear actuator functional model



Conventional system: Actuator functional model

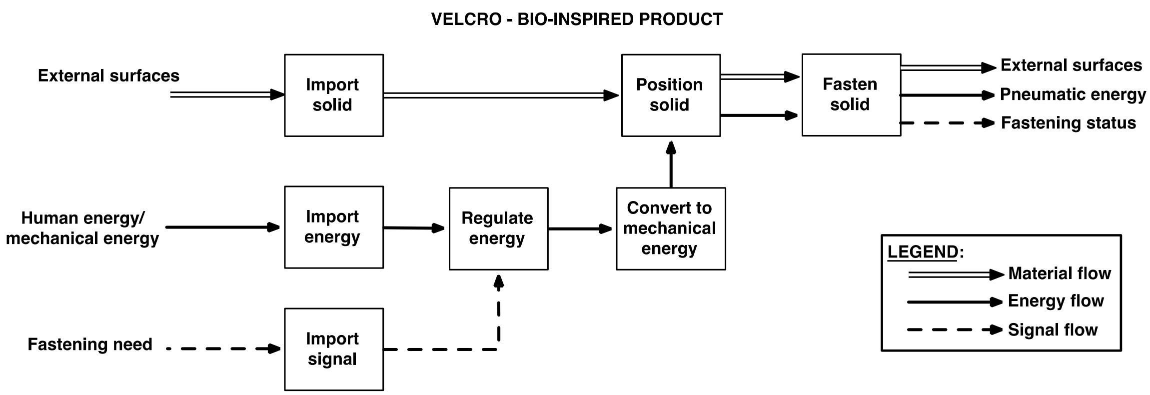


Morph matrix

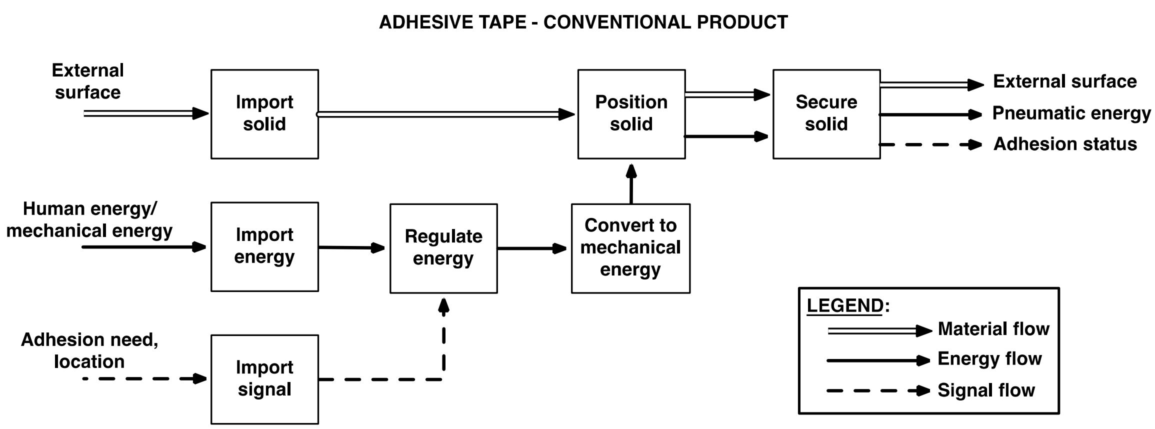
Function-Flow Pairs			Components	
Natural/Biomimetic Solution	**Conventional Engineered Solution**	**Primary Functionality**	**Natural/Biomimetic Solution**	**Conventional Engineered Solution**
Import electrical energy	Import electrical energy and/or hydraulic energy	Import	Battery	Battery
Regulate electrical energy	Regulate electrical energy	Regulate	Circuit Board	Circuit board
Convert electrical to mechanical energy	Convert electrical to mechanical energy	Convert	Piezoelectric transducer (PZT)	Motor
X	Convert rotational to linear motion	Convert	X	Gears
Import solid	Import solid	Import	Actuator clamps	Actuator plate
Import solid	Import solid	Import	Guide rails	Guide rod/rail
Position solid	Position solid	Position	Actuator clamps	Actuator plate
Import control signal	Import control signal	Import	Circuit board	Circuit board
Process control signal	Process control signal	Process	Circuit board	Circuit board
Guide solid	Guide solid	Guide	PZT, actuator clamps and guide rails	Actuator plate, motor, and actuator plate housing
Export solid	Export solid	Export	Actuator clamps	Actuator plate

7. Cocklebur plant seed and Velcro®

Bio-inspired system: Velcro® fastener functional model



Conventional system: Adhesive tape functional model

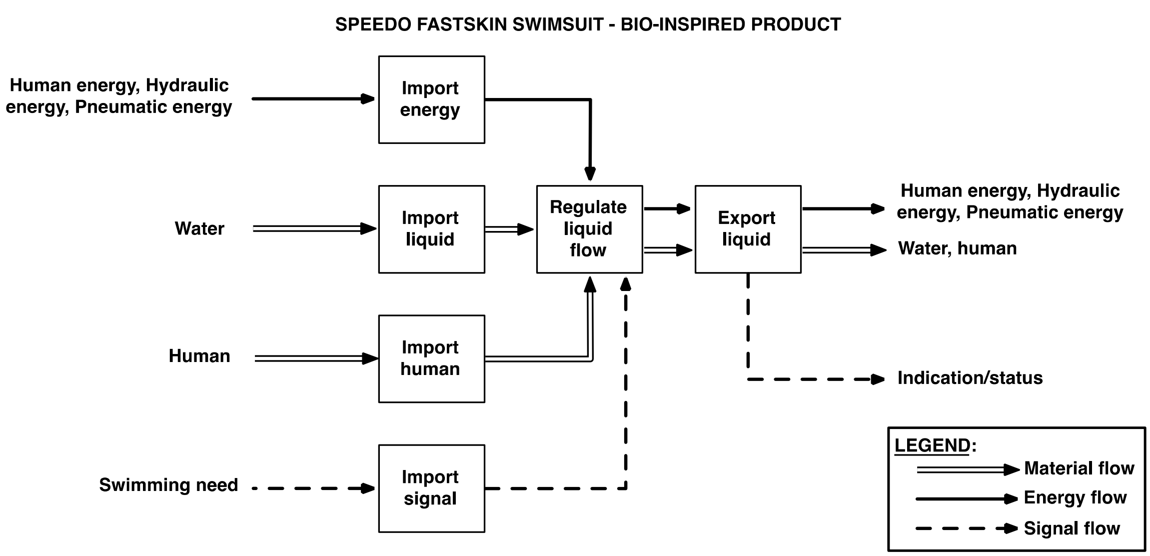


Morph matrix

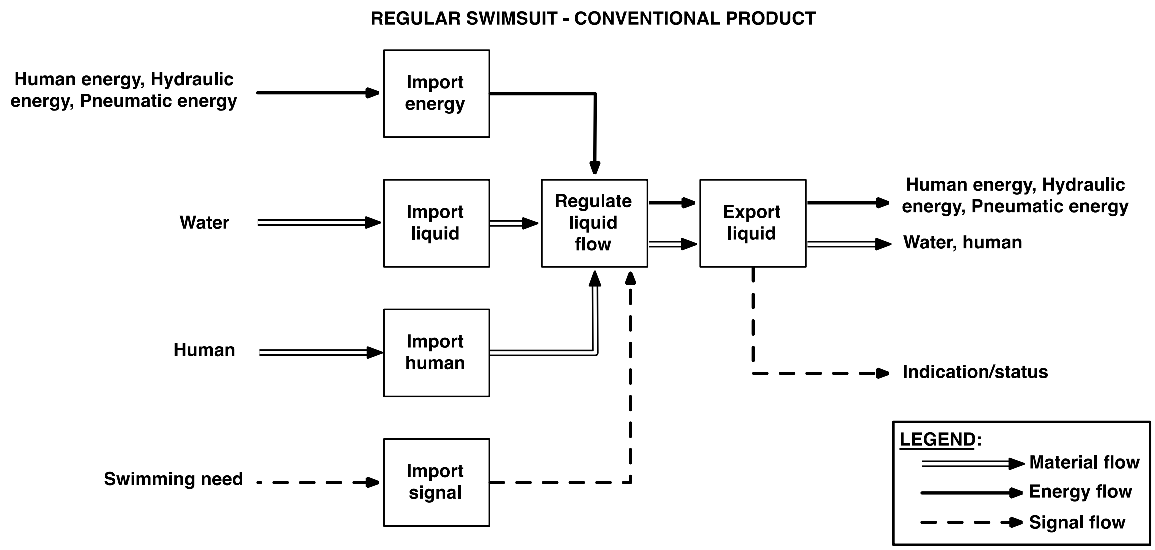
Function-Flow Pairs		Primary Functionality	Components	
Natural/Biomimetic Solution	**Conventional Engineered Solution**		**Natural/Biomimetic Solution**	**Conventional Engineered Solution**
Import solid (external surface)	Import solid (external surface)	Import	Human/robotic arm	Human/robotic arm
Import human/mechanical energy	Import human/mechanical energy	Import	Human/robotic arm	Human/robotic arm
Regulate energy	Regulate energy	Regulate	Brain/circuit	Brain/circuit
Convert to mechanical energy	Convert to mechanical energy	Convert	Human	Human
Import signal	Import signal	Import	Brain/circuit	Brain/circuit
Position solid	Position solid	Position	Human/robotic arm	Human/robotic arm
Fasten solid	Fasten solid	Fasten	Hooks attach to fibers on mating strap	Chemical coating

8. Shark's skin and Speedo FastSkin® swimsuit

Bio-inspired system: Speedo FastSkin® swimsuit functional model



Conventional system: Regular swimsuit functional model

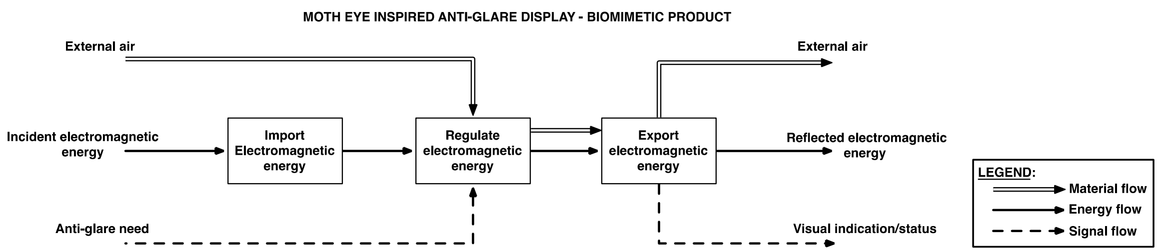


Morph matrix

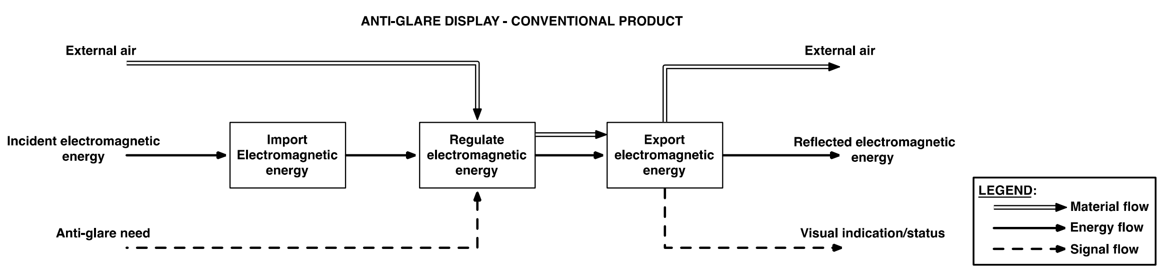
Function-Flow Pairs		Primary Functionality	Components	
Natural/Biomimetic Solution	**Conventional Engineered Solution**		**Natural/Biomimetic Solution**	**Conventional Engineered Solution**
Import human, hydraulic, and pneumatic energy	Import human, hydraulic, and pneumatic energy	Import	Human body and suit surface	Human body and suit surface
Import liquid	Import liquid	Import	Suit surface	Suit surface
Import human	Import human	Import	Suit surface, Human body	Suit surface, Human body
Import signal	Import signal	Import	Brain	Brain
Regulate liquid flow	Regulate liquid flow	Regulate	Surface texture of swimsuit, suit fit	Suit fit
Export liquid	Export liquid	Export	Suit surface	Suit surface

9. Moth's eyes and bio-inspired anti-glare displays

Bio-inspired system: Moth eye inspired anti-glare display functional model



Conventional system: Conventional anti-glare display functional model

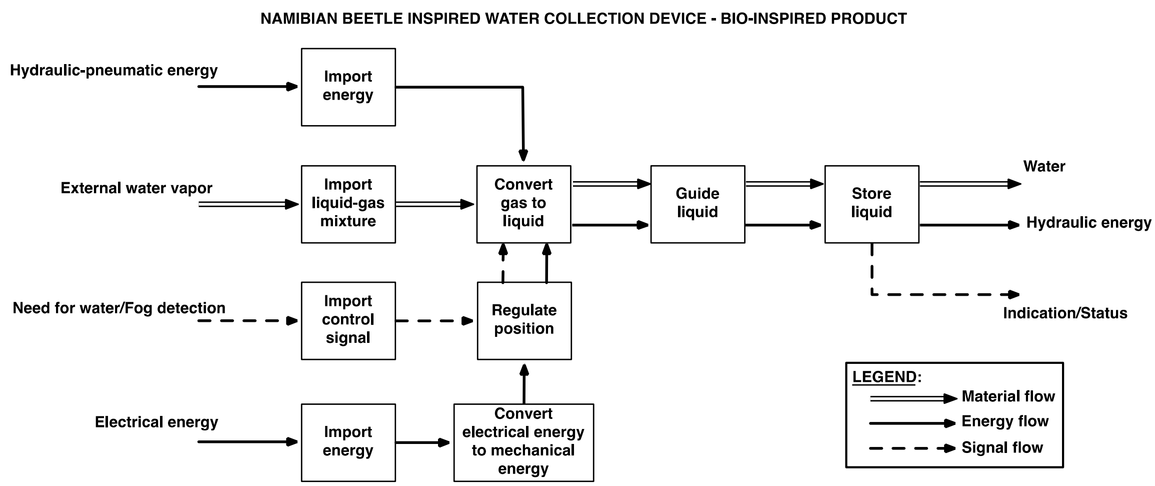


Morph matrix

Function-Flow Pairs		Primary Functionality	Components	
Natural/Biomimetic Solution	Conventional Engineered Solution		Natural/Biomimetic Solution	Conventional Engineered Solution
Import electromagnetic energy	Import electromagnetic energy	Import	Display surface	Display surface
Regulate electromagnetic energy	Regulate electromagnetic energy	Regulate	Micro-structural bumps on display surface	Chemical coatings, multi-layered composites
Export electromagnetic energy	Export electromagnetic energy	Export	Display surface	Display surface

10. Namibian beetle's water harvesting mechanism and bio-inspired water harvester

Bio-inspired system: Namibian beetle inspired water harvester functional model

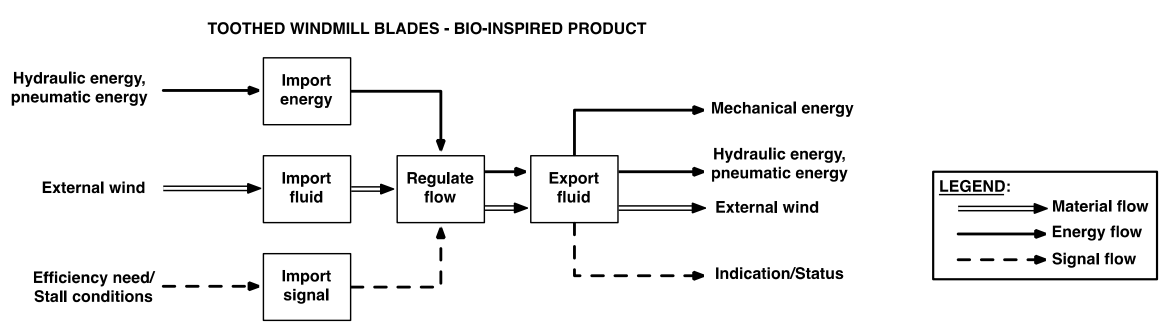


Conventional system: None

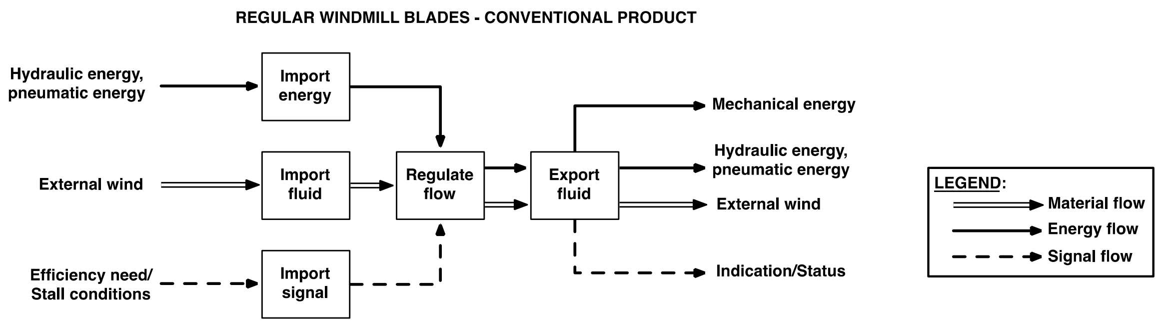
Morph matrix: None

11. Humpback whale's flipper and bio-inspired turbine blades

Bio-inspired system: Whale flipper inspired turbine blade functional model



Conventional system: Conventional turbine blade functional model

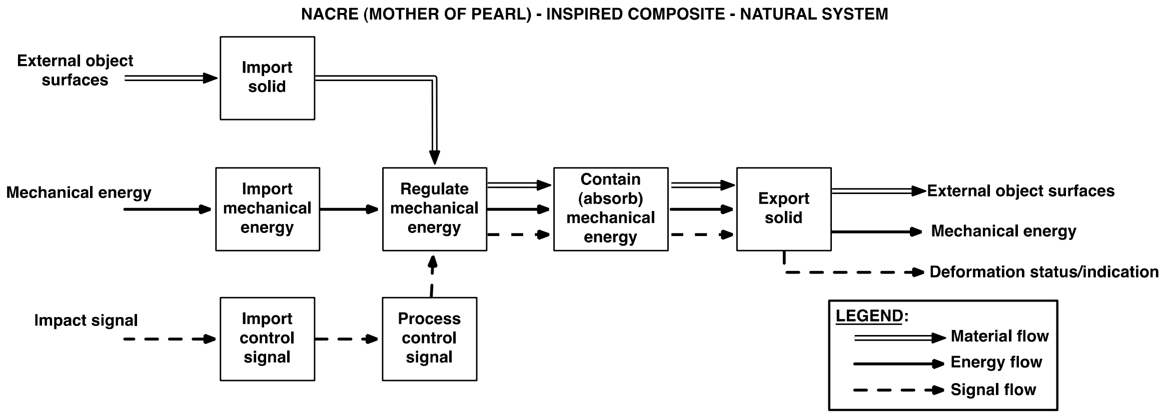


Morph matrix

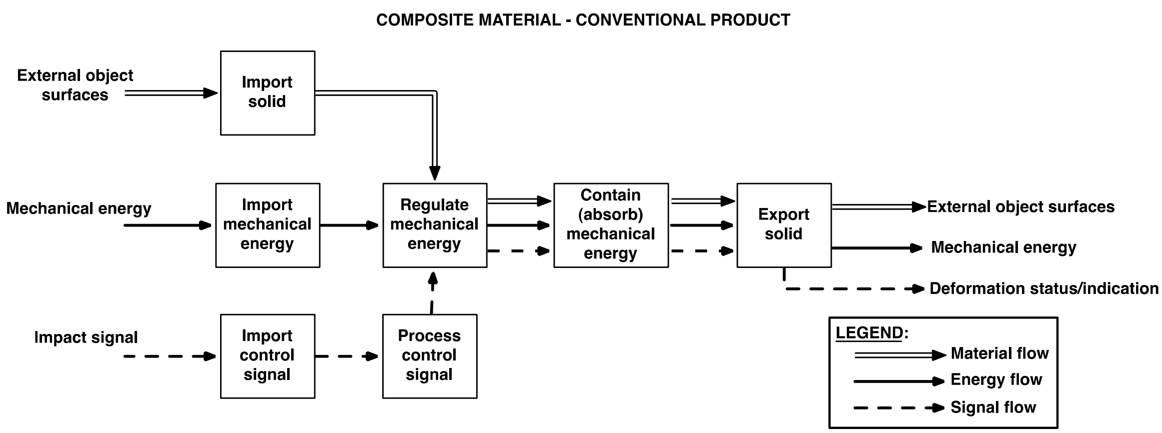
Function-Flow Pairs		Primary Functionality	Components	
Natural/Biomimetic Solution	**Conventional Engineered Solution**		**Natural/Biomimetic Solution**	**Conventional Engineered Solution**
Import hydraulic and pneumatic energy	Import hydraulic and pneumatic energy	Import	Blade surface	Blade surface
Import fluid (airflow)	Import fluid (airflow)	Import	Blade surface	Blade surface
Import signal	Import signal	Import	Circuit board	Circuit board
Regulate flow	Regulate flow	Regulate	Blade surface and tubercles/toothed bumps on leading edge	Blade surface and leading edge
Export fluid	Export fluid	Export	Blade surface trailing edge	Blade surface trailing edge

12. Mother-of-Pearl (or Nacre) and bio-inspired composite

Bio-inspired system: Nacre-inspired composite material functional model



Conventional system: Conventional material functional model

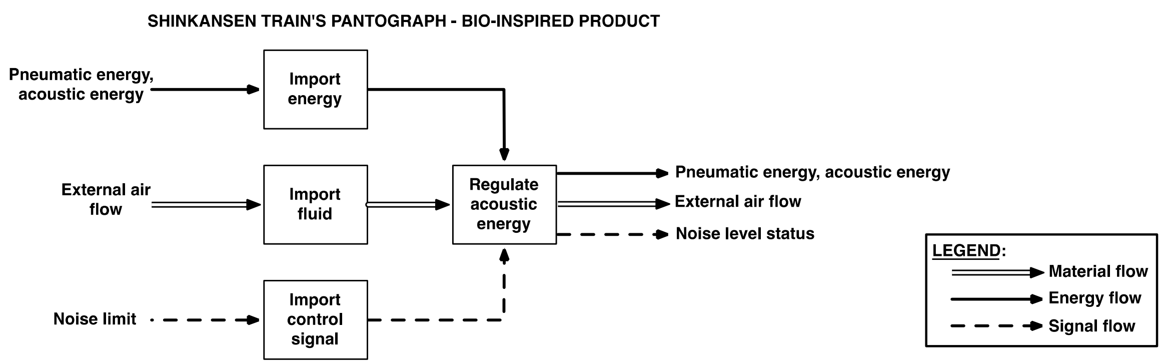


Morph matrix

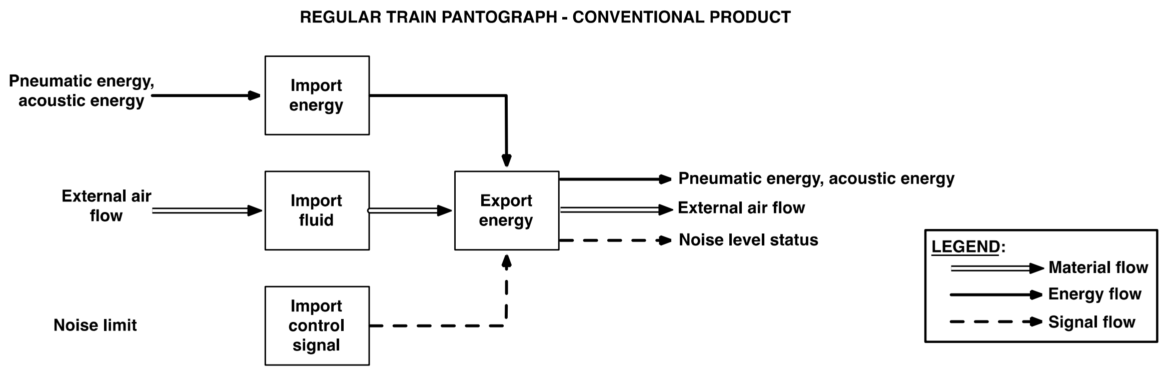
Function-Flow Pairs		Primary Functionality	Components	
Natural/Biomimetic Solution	**Conventional Engineered Solution**		**Natural/Biomimetic Solution**	**Conventional Engineered Solution**
Import external object surfaces	Import external object surfaces	Import	Composite surface	Composite surface
Import mechanical energy	Import mechanical energy	Import	Composite surface	Composite surface
Import signal	Import signal	Import	Composite surface, cells	Composite surface, external sensors
Process control signal	Process control signal	Process	Brain	External controller device (if part of system)
Regulate mechanical energy	Regulate mechanical energy	Regulate	Highly ordered layered structure of constituents (Aluminum oxide and polymethyle methacrylate)	Composite of different constituents
Contain (absorb) mechanical energy (resist rupture of surface with holes in it)	Contain (absorb) mechanical energy (resist rupture of surface with holes in it)	Contain	Highly ordered layered structure of constituents (Aluminum oxide and polymethyle methacrylate)	Composite of different constituents
Export signal	Export signal	Export	Surface, cells	Surface, external sensor

13. Owl flight feathers and Shinkansen train's bio-inspired pantograph design

Bio-inspired system: Bio-inspired noise reducing pantograph design functional model



Conventional system: Conventional train pantograph functional model

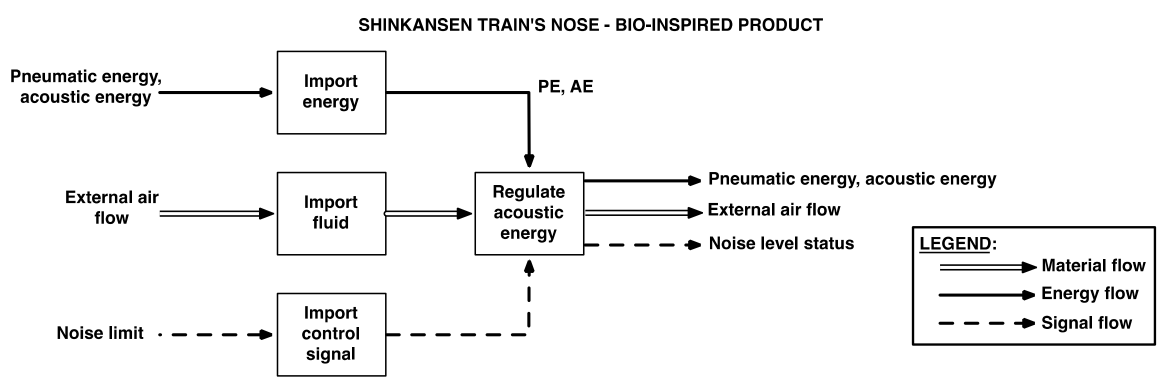


Morph matrix

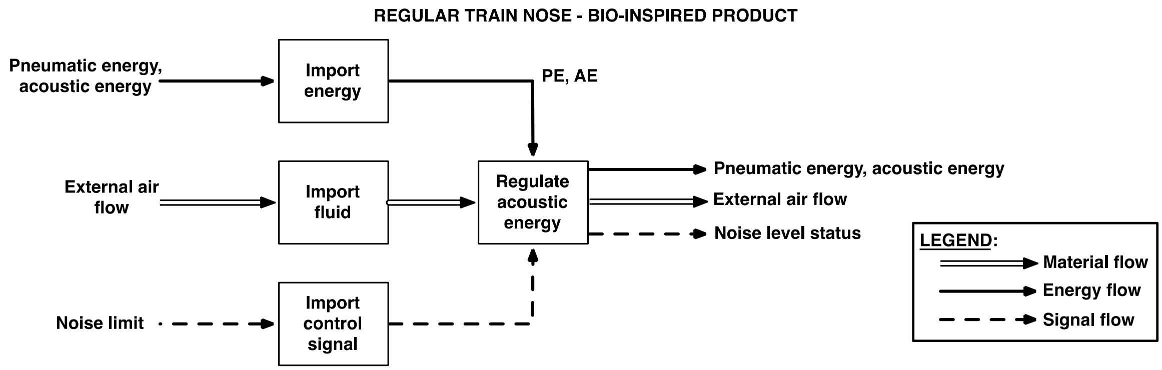
Function-Flow Pairs		Primary Functionality	Components	
Natural/Biomimetic Solution	Conventional Engineered Solution		Natural/Biomimetic Solution	Conventional Engineered Solution
Import pneumatic and acoustic energy	Import pneumatic and acoustic energy	Import	Nose surface	Nose surface
Import fluid (air)	Import fluid (air)	Import	Nose surface	Nose surface
Import signal	Import signal	Import	Sensors	Sensors
Regulate acoustic energy	Regulate acoustic energy	Regulate	Serrated edges on pantograph surface, shape	Shape

14. Kingfisher beak and Shinkansen train's nose design

Bio-inspired system: Shinkansen train's noise reducing nose design functional model



Conventional system: Conventional train nose functional model

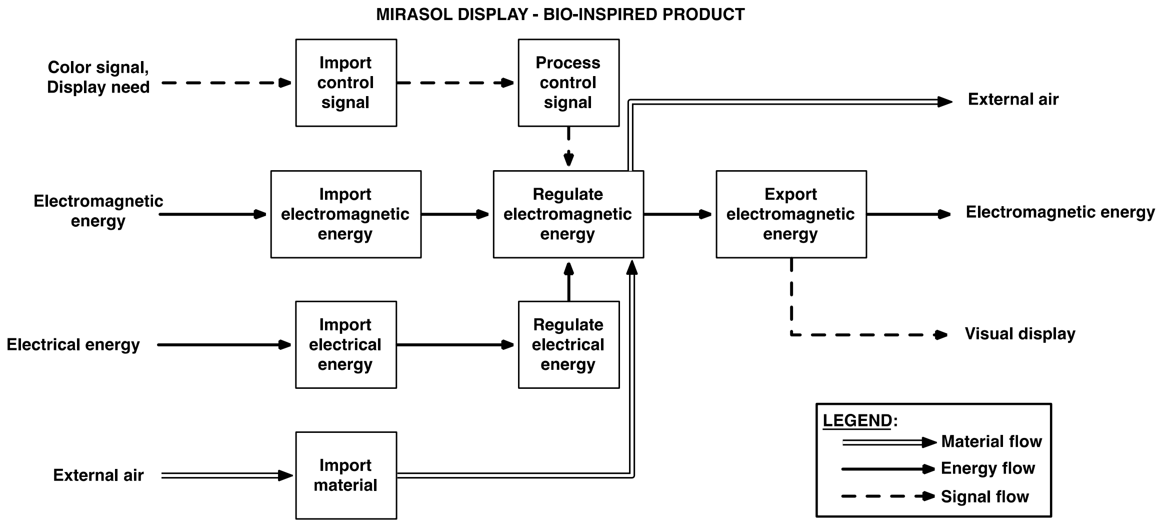


Morph matrix

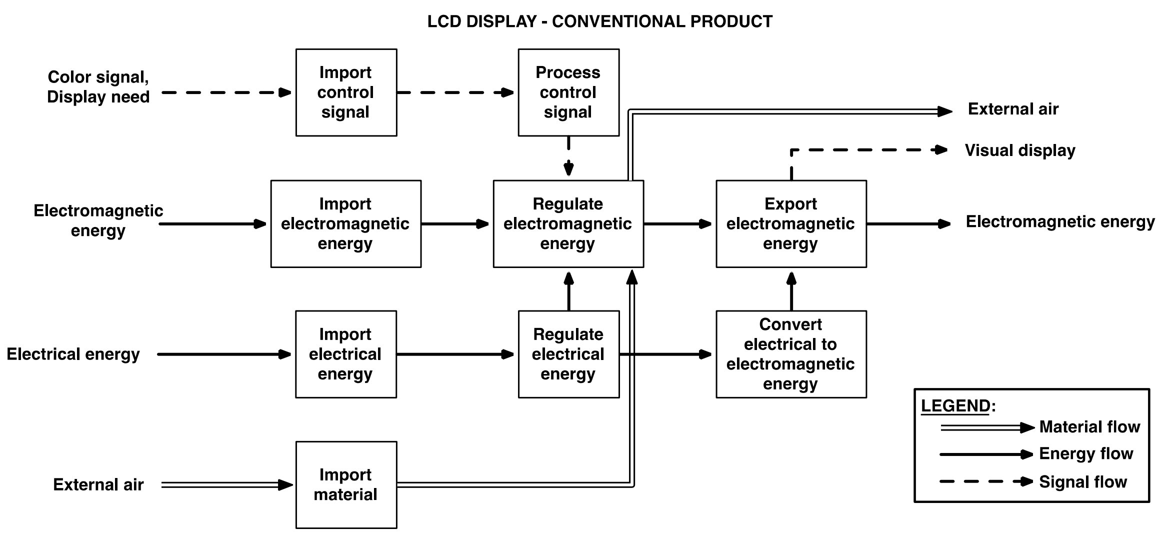
Function-Flow Pairs		Primary Functionality	Components	
Natural/Biomimetic Solution	**Conventional Engineered Solution**		**Natural/Biomimetic Solution**	**Conventional Engineered Solution**
Import pneumatic and acoustic energy	Import pneumatic and acoustic energy	Import	Nose surface	Nose surface
Import fluid (air)	Import fluid (air)	Import	Nose surface	Nose surface
Import signal	Import signal	Import	Sensors	Sensors
Regulate acoustic energy	Regulate acoustic energy	Regulate	Nose shape	None

15. Butterfly wing's color display method and Mirasol® Qualcom's display

Bio-inspired system: Butterfly wing inspired Mirasol® display functional model



Conventional system: LCD display functional model

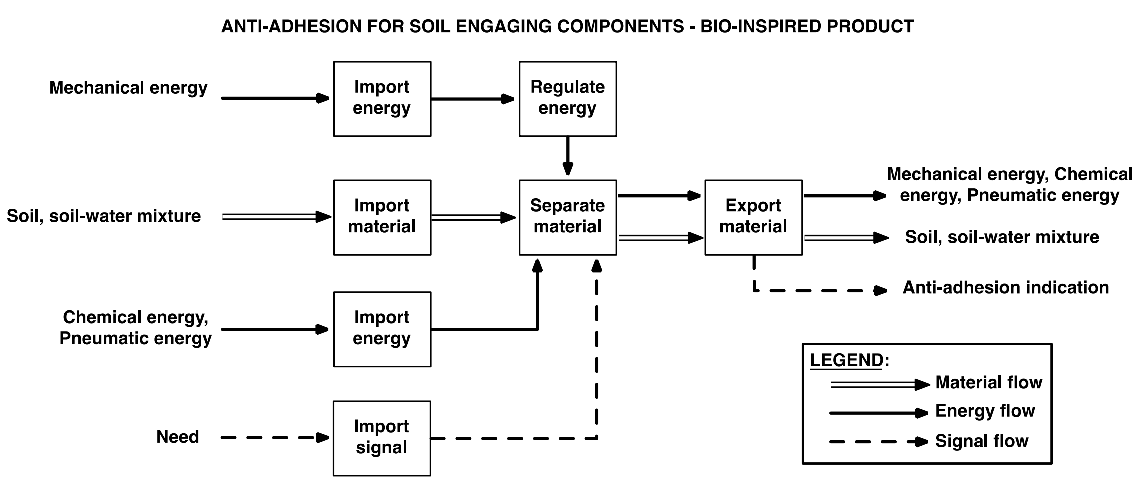


Morph matrix

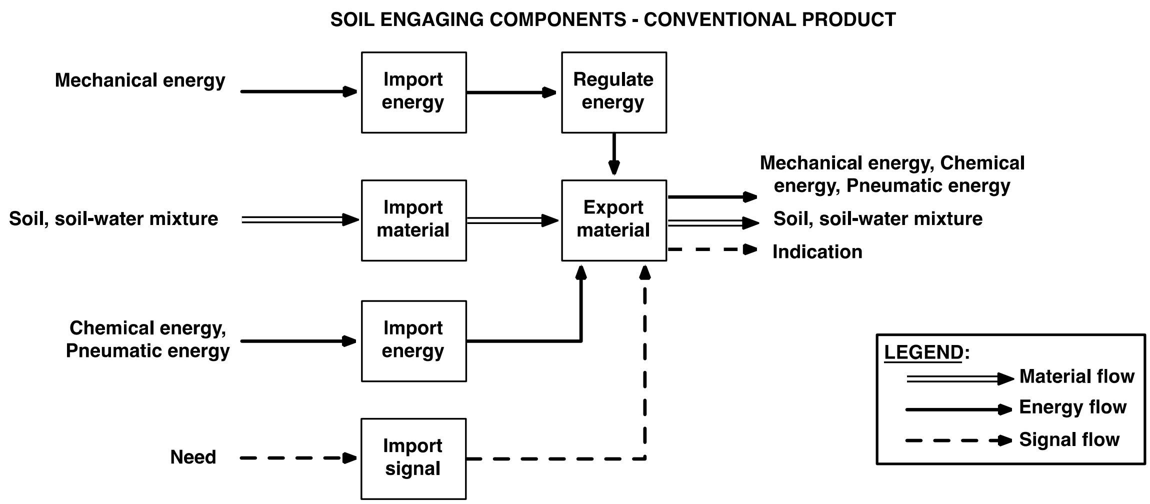
Function-Flow Pairs		Primary Functionality	Components	
Natural/Biomimetic Solution	Conventional Engineered Solution		Natural/Biomimetic Solution	Conventional Engineered Solution
Import control signal (required colors)	Import control signal (required colors)	Import	Control panel/image input	Control panel/image input
Process control signal	Process control signal	Process	Circuit board	Circuit board
Import electromagnetic energy (incident light)	Import electromagnetic energy (incident light)	Import	Display surface	Display surface
Regulate electromagnetic energy (incident light)	Regulate electromagnetic energy (incident light)	Regulate	Discrete Interferometric Modulator (IMOD) elements	Liquid Crystal Mixtures (LCD)
Import electrical energy	Import electrical energy	Import	Battery/Power source	Battery/Power source
Regulate electrical energy	Regulate electrical energy	Regulate	Circuit board	Circuit board
Import material (external air)	Import material (external air)	Import	Display surface	Display surface
X	Convert electrical to electromagnetic energy	Convert	X	Backlight
Export electromagnetic energy (reflected light)	Export electromagnetic energy (reflected light)	Export	IMOD and Display surface	Liquid crystal mixture and Display surface

16. Soil-adhesion in burrowing animals and bio-inspired design of soil-engaging components

Bio-inspired system: Bio-inspired design of soil-engaging components' functional model



Conventional system: Soil-engaging components' functional model

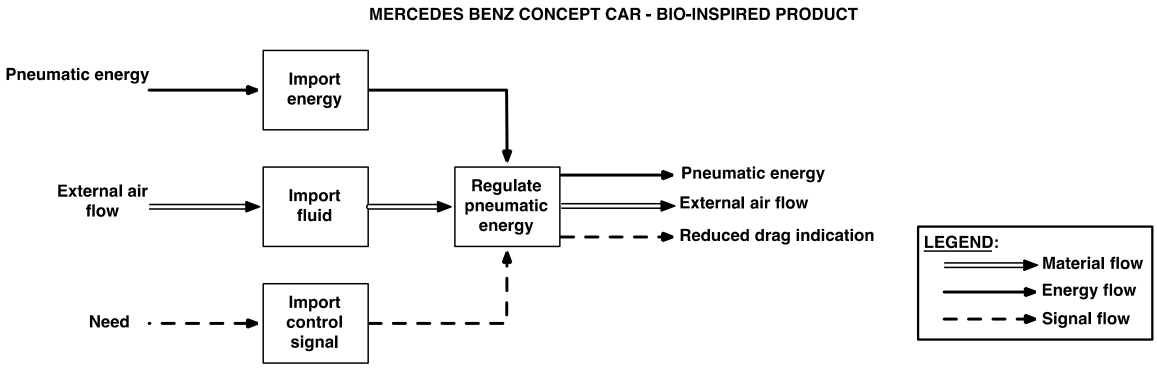


Morph matrix

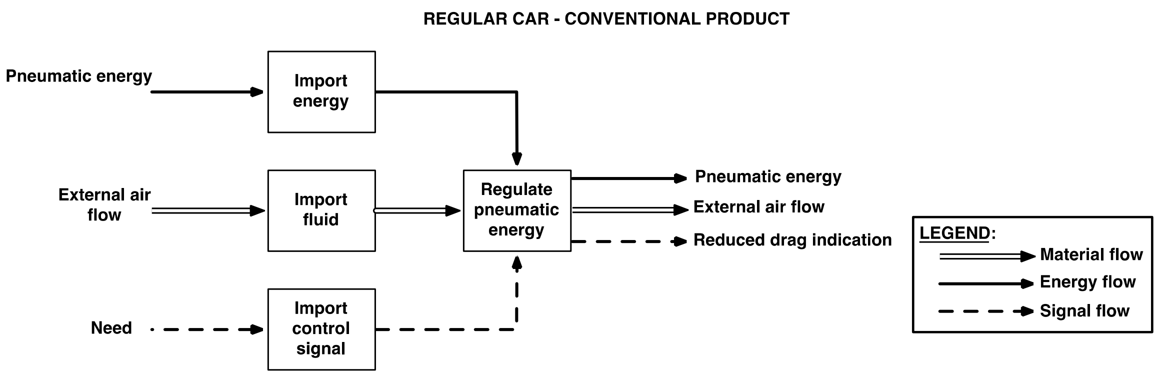
Function-Flow Pairs		Primary Functionality	Components	
Natural/Biomimetic Solution	**Conventional Engineered Solution**		**Natural/Biomimetic Solution**	**Conventional Engineered Solution**
Import mechanical energy	Import mechanical energy	Import	Engine	Engine
Import material (soil, soil-water mixture)	Import material (soil, soil-water mixture)	Import	Soil engaging component surface	Soil engaging component surface
Import chemical and pneumatic energy	Import chemical and pneumatic energy	Import	Component surface	Component surface
Import signal	Import signal	Import	Circuit board	Circuit board
Regulate mechanical energy	Regulate mechanical energy	Regulate	Actuators, Motors	Actuators, Motors
Separate material (soil, soil-water mixture)	Separate material (soil, soil-water mixture)	Separate	Surface morphology (bumps and ridges), type, and material	Surface material and type
Export material (soil, soil-water mixture)	Export material (soil, soil-water mixture)	Export	Component surface	Component surface

17. Boxfish and bio-inspired Mercedes® concept car design

Bio-inspired system: Box fish inspired concept car design functional model



Conventional system: Conventional car design functional model

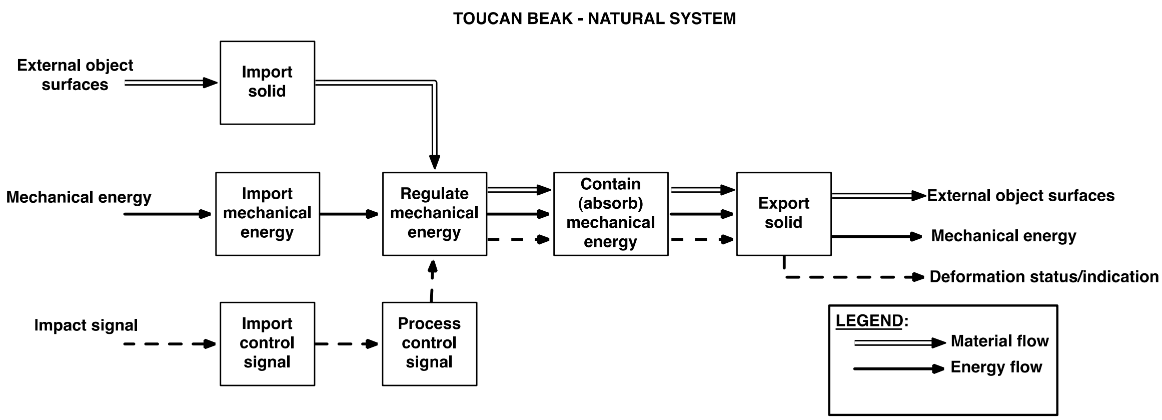


Morph matrix

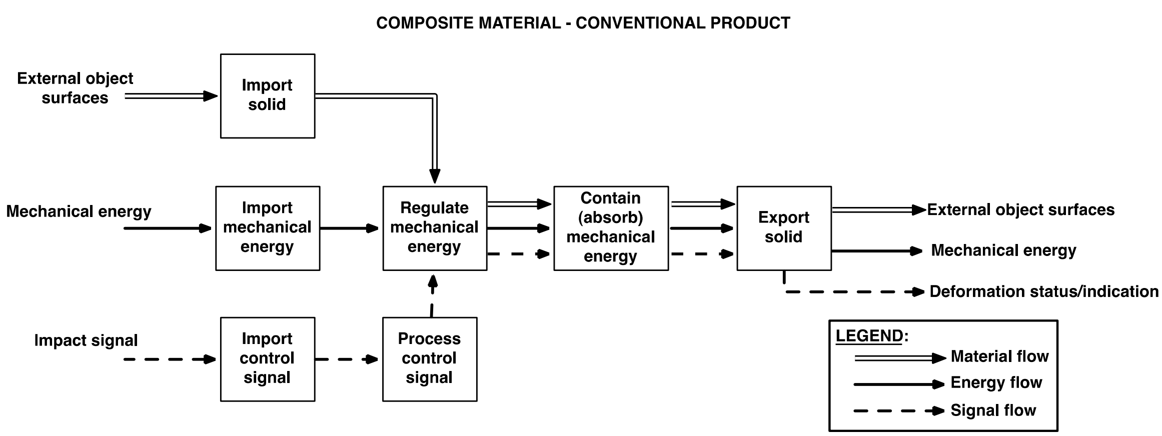
Function-Flow Pairs		Primary Functionality	Components	
Natural/Biomimetic Solution	Conventional Engineered Solution		Natural/Biomimetic Solution	Conventional Engineered Solution
Import pneumatic and acoustic energy	Import pneumatic and acoustic energy	Import	Car surface	Car surface
Import fluid (air)	Import fluid (air)	Import	Car surface	Car surface
Import signal	Import signal	Import		
Regulate acoustic energy	Regulate acoustic energy	Regulate	Box-fish inspired shape	Car shape

18. Toucan's beak and bio-inspired composite material

Bio-inspired system: Toucan beak composite material functional model



Conventional system: Regular composite material functional model

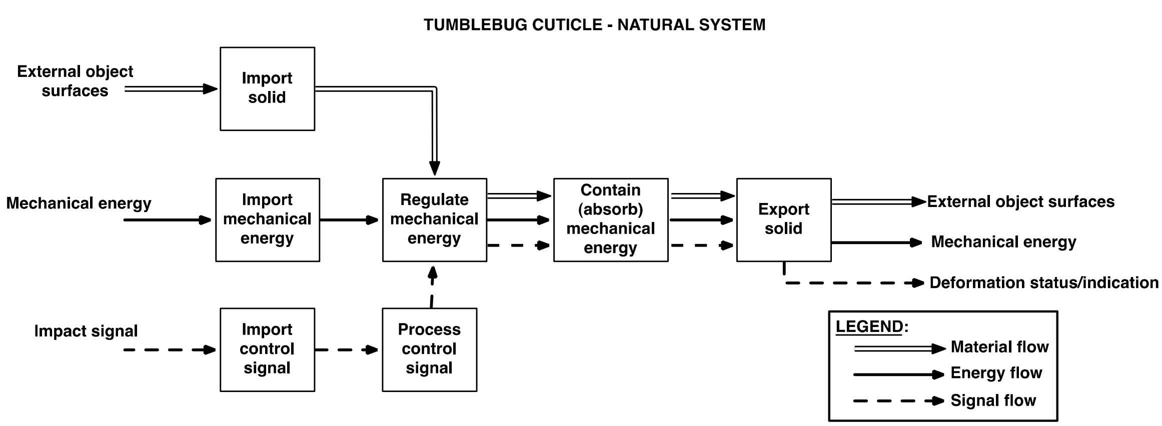


Morph matrix

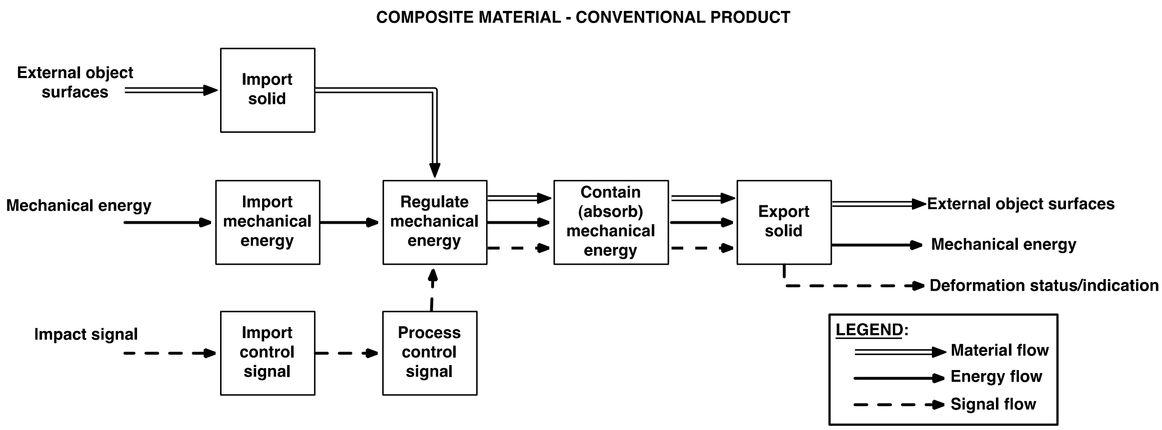
Function-Flow Pairs		Primary Functionality	Components	
Natural/Biomimetic Solution	**Conventional Engineered Solution**		**Natural/Biomimetic Solution**	**Conventional Engineered Solution**
Import external object surfaces	Import external object surfaces	Import	Composite surface	Composite surface
Import mechanical energy	Import mechanical energy	Import	Composite surface	Composite surface
Import signal	Import signal	Import	Composite surface, cells	Composite surface, external sensors
Process control signal	Process control signal	Process	Brain	External controller device (if part of system)
Regulate mechanical energy	Regulate mechanical energy	Regulate	Structured composite: Rigid foam sandwiched by keratin protein	Composite of different constituents
Contain (absorb) mechanical energy	Contain (absorb) mechanical energy	Contain	Rigid foam (inside the keratin shell)	Constituent matrix
Export signal	Export signal	Export	Surface, cells	Surface, external sensor

19. Circumcolumnar microstructure of Tumblebug cuticle and bio-inspired composite

Bio-inspired system: Tumblebug cuticle composite material functional model



Conventional system: Regular composite material functional model

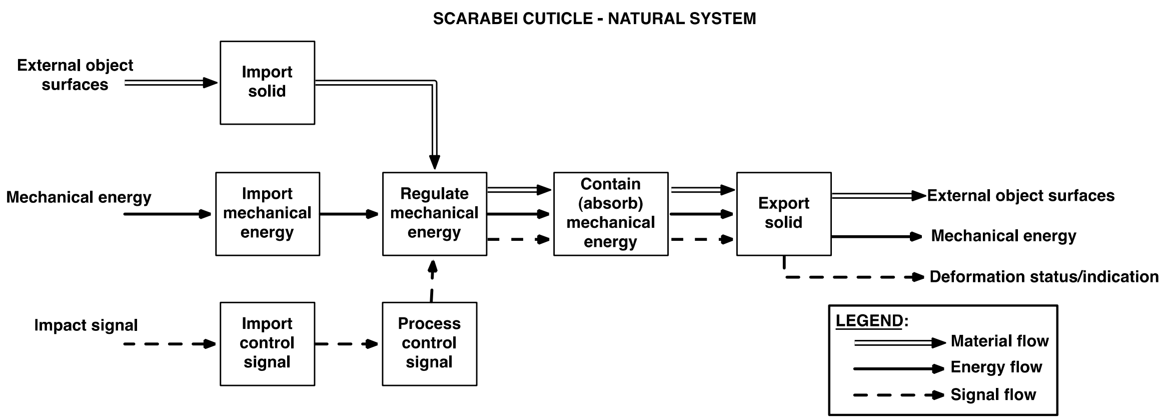


Morph matrix

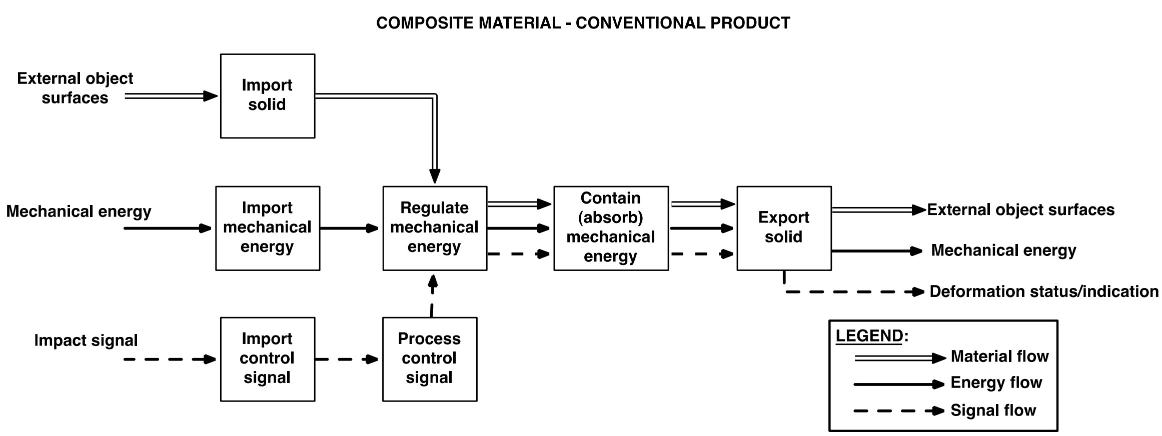
Function-Flow Pairs		Primary Functionality	Components	
Natural/Biomimetic Solution	Conventional Engineered Solution		Natural/Biomimetic Solution	Conventional Engineered Solution
Import external object surfaces	Import external object surfaces	Import	Composite surface	Composite surface
Import mechanical energy	Import mechanical energy	Import	Composite surface	Composite surface
Import signal	Import signal	Import	Composite surface, cells	Composite surface, external sensors
Process control signal	Process control signal	Process	Brain	External controller device (if part of system)
Regulate mechanical energy	Regulate mechanical energy	Regulate	Internal circumcolumnar microstructure arrangement of chitin fibers and sclerotized protein matrixes	Composite of different constituents
Contain (absorb) mechanical energy (resist rupture of surface with holes in it)	Contain (absorb) mechanical energy (resist rupture of surface with holes in it)	Contain	Internal circumcolumnar microstructure arrangement of chitin fibers and sclerotized protein matrixes	Composite of different constituents
Export signal	Export signal	Export	Surface, cells	Surface, external sensor

20. Helicoidal microstructure of Scarabaei cuticle

Bio-inspired system: Scarabaei cuticle composite material functional model



Conventional system: Regular composite material functional model

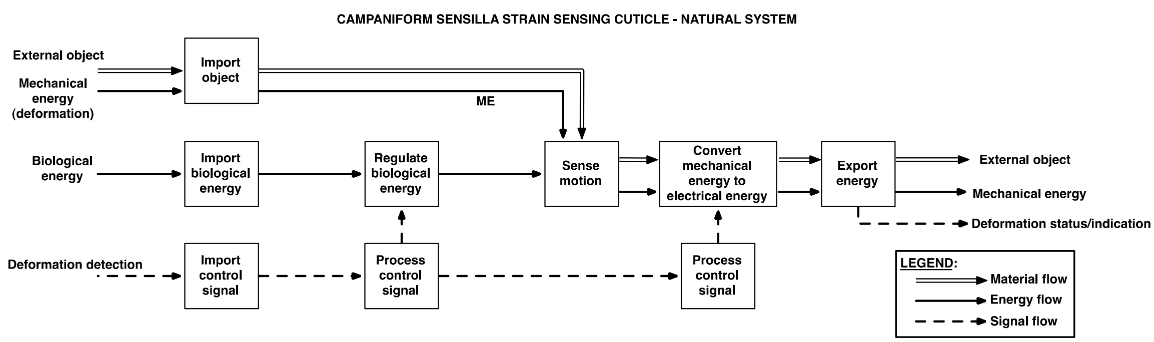


Morph matrix

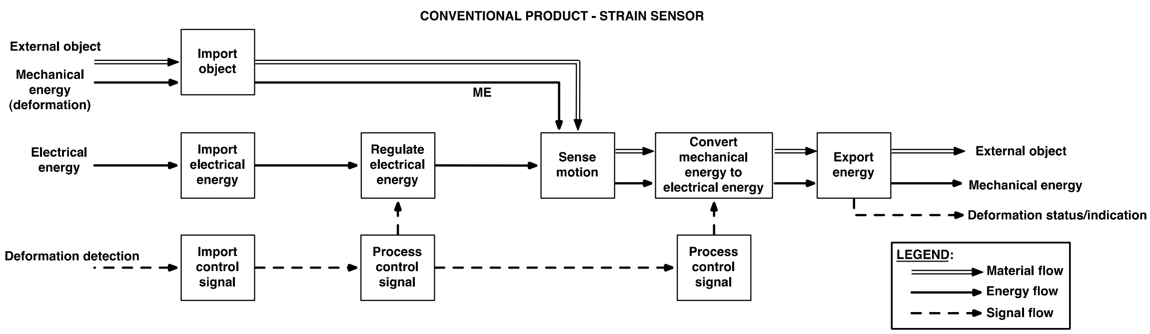
Function-Flow Pairs		Primary Functionality	Components	
Natural/Biomimetic Solution	**Conventional Engineered Solution**		**Natural/Biomimetic Solution**	**Conventional Engineered Solution**
Import external object surfaces	Import external object surfaces	Import	Composite surface	Composite surface
Import mechanical energy	Import mechanical energy	Import	Composite surface	Composite surface
Import signal	Import signal	Import	Composite surface, cells	Composite surface, external sensors
Process control signal	Process control signal	Process	Brain	External controller device (if part of system)
Regulate mechanical energy	Regulate mechanical energy	Regulate	Helicoidal structure of chitin-fiber layers and sclerous protein matrices	Composite of different constituents
Contain (absorb) mechanical energy (high strength resistance)	Contain (absorb) mechanical energy (high strength resistance)	Contain	Helicoidal structure of chitin-fiber layers and sclerous protein matrices	Composite of different constituents
Export signal	Export signal	Export	Surface, cells	Surface, external sensor

21. Campaniform Sensilla: Measuring Strain from the Deformation of Holes

Natural system: Campaniform sensilla's strain sensing cuticle functional model



Conventional system: Conventional strain sensor functional model

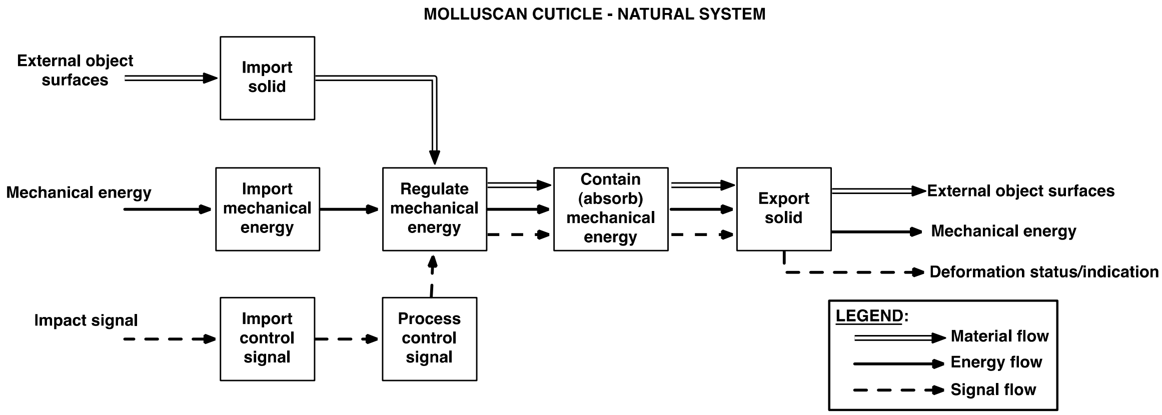


Morph matrix

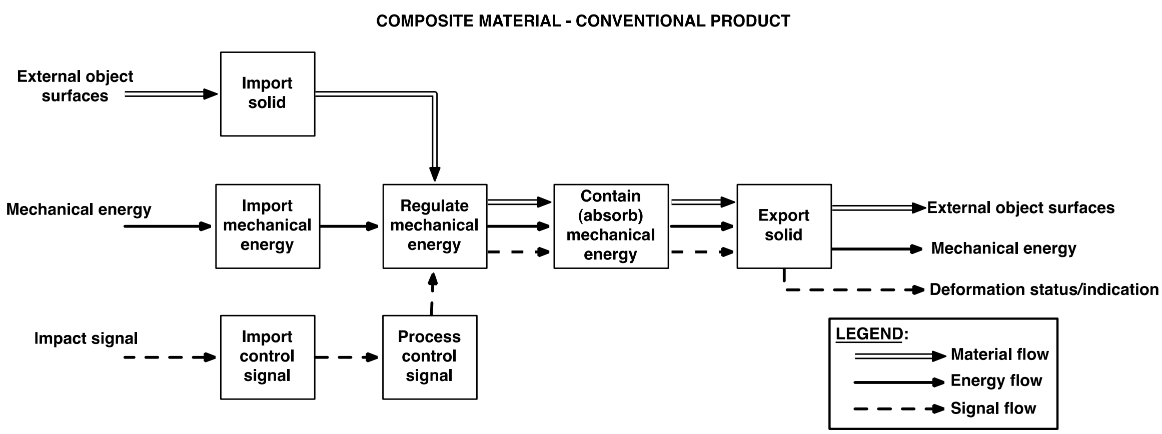
Function-Flow Pairs			Components	
Natural/Biomimetic Solution	**Conventional Engineered Solution**	**Primary Functionality**	**Natural/Biomimetic Solution**	**Conventional Engineered Solution**
External object	External object	Import	Cuticle surface	Sensor surface
Mechanical energy (deformation)	Mechanical energy (deformation)	Import	Cuticle surface	Sensor surface
Biological energy	Electrical energy	Import	Brain, cells	Battery, Circuit
Deformation signal	Deformation signal	Import	Cuticle cells	Sensor surface
Biological energy regulation	Electrical energy regulation	Regulate	Cells, muscles	Circuit board
Deformation signal	Deformation signal	Process	Brain	Circuit board
Sense deformation	Sense deformation	Sense	Campaniform Sensillum – hole in cuticle's shape change based on external force	Embedded objects in sensor surface or external devices
Convert mechanical energy to electrical energy	Convert mechanical energy to electrical energy	Convert	Cells, brain	Sensory devices and circuits
Deformation signal	Deformation signal	Process	Brain	Circuit board
Export signal, mechanical energy, and external object	Export signal, mechanical energy, and external object	Export	Cells, neurons, and Cuticle surface	Circuit board and sensor surface

22. Molluscan or bivala shell

Bio-inspired system: Molluscan shell composite material functional model



Conventional system: Regular composite material functional model

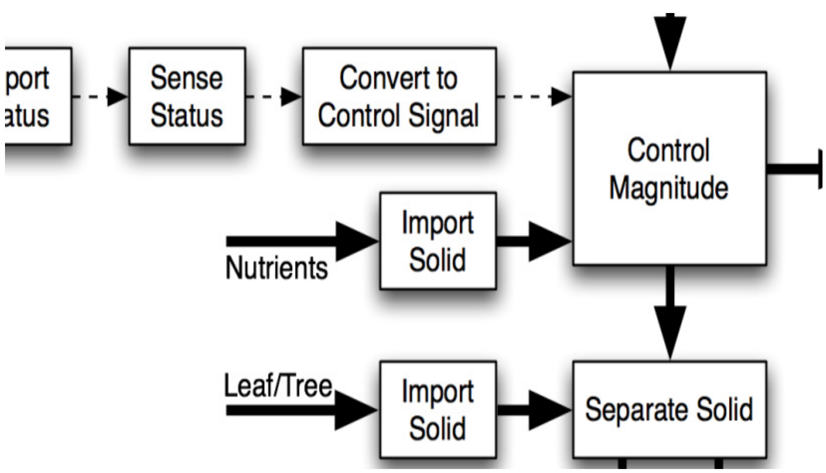


Morph matrix

Function-Flow Pairs		Primary Functionality	Components	
Natural/Biomimetic Solution	Conventional Engineered Solution		Natural/Biomimetic Solution	Conventional Engineered Solution
Import external object surfaces	Import external object surfaces	Import	Composite surface	Composite surface
Import mechanical energy	Import mechanical energy	Import	Composite surface	Composite surface
Import signal	Import signal	Import	Composite surface, cells	Composite surface, external sensors
Process control signal	Process control signal	Process	Brain	External controller device (if part of system)
Regulate mechanical energy	Regulate mechanical energy	Regulate	Optimized structure: Laminated and parallel layered arrangement of aragonites (a form of calcium carbonate)	Composite of different constituents
Contain (absorb) mechanical energy (high strength resistance)	Contain (absorb) mechanical energy (high strength resistance)	Contain	Optimized structure: Laminated and parallel layered arrangement of aragonites (a form of calcium carbonate)	Composite of different constituents
Export signal	Export signal	Export	Surface, cells	Surface, external sensor

23. Plant abscission and bio-inspired micro-screw assembly method

Natural system: Plant abscission functional model [3]



Conventional system: None

Morph matrix: None

VITA

Name: Anosh Porus Wadia

Address: Mechanical Engineering Department,
Texas A&M University,
College Station, TX – 77843-3123

Email address: anoshw2@yahoo.com

Education: Master of Science, Texas A&M University, College Station, August 2011

Bachelor of Science, Texas A&M University, College Station, August 2009

Higher Secondary Certificate Examination (Science), St. Xavier's College, Mumbai, February 2004

All India Secondary School Examination (CBSE), Rajkumar College, Rajkot, April 2002