

# Creative design inspired by biological knowledge: Technologies and methods

Runhua TAN (✉), Wei LIU, Guozhong CAO

*School of Mechanical Engineering, Hebei University of Technology, Tianjin 300401, China; National Engineering Research Center for Technological Innovation Method and Tool, Hebei University of Technology, Tianjin 300401, China*

E-mail: rhtan@hebut.edu.cn

Yuan SHI

*Department of Mechanical Engineering, Politecnico di Milano, Milan 20156, Italy*

*Front. Mech. Eng.*, **Just Accepted Manuscript** • DOI: 10.1007/s11465-018-0511-0

<http://journal.hep.com.cn> on April 9, 2018

© Higher Education Press and Springer-Verlag GmbH Germany, part of Springer Nature 2018

## **Just Accepted**

This is a “Just Accepted” manuscript, which has been examined by the peer-review process and has been accepted for publication. A “Just Accepted” manuscript is published online shortly after its acceptance, which is prior to technical editing and formatting and author proofing. Higher Education Press (HEP) provides “Just Accepted” as an optional and free service which allows authors to make their results available to the research community as soon as possible after acceptance. After a manuscript has been technically edited and formatted, it will be removed from the “Just Accepted” Web site and published as an Online First article. Please note that technical editing may introduce minor changes to the manuscript text and/or graphics which may affect the content, and all legal disclaimers that apply to the journal pertain. In no event shall HEP be held responsible for errors or consequences arising from the use of any information contained in these “Just Accepted” manuscripts. To cite this manuscript please use its Digital Object Identifier (DOI(r)), which is identical for all formats of publication.”

# Creative design inspired by biological knowledge: Technologies and methods

© Higher Education Press and Springer-Verlag GmbH Germany, part of Springer Nature 2018

Received September 1, 2017; accepted November 28, 2017

Runhua TAN (✉), Wei LIU, Guozhong CAO

School of Mechanical Engineering, Hebei University of Technology, Tianjin 300401, China; National Engineering Research Center for Technological Innovation Method and Tool, Hebei University of Technology, Tianjin 300401, China

E-mail: [rhtan@hebut.edu.cn](mailto:rhtan@hebut.edu.cn)

Yuan SHI

Department of Mechanical Engineering, Politecnico di Milano, Milan 20156, Italy

**Abstract** Biological knowledge is becoming an important source of inspiration for developing creative solutions to engineering design problems and even has a huge potential in formulating ideas that can help firms compete successfully in a dynamic market. To identify the technologies and methods that can facilitate the development of biologically inspired creative designs, this research briefly reviews the existing biological-knowledge-based theories and methods and examines the application of biological-knowledge-inspired designs in various fields. Afterward, this research thoroughly examines the four dimensions of key technologies that underlie the biologically inspired design (BID) process. This research then discusses the future development trends of the BID process before presenting the conclusions.

**Keywords** creative design, biologically inspired methods, key technologies

## 1 Introduction

Innovation is becoming a significant attribute that helps firms develop and survive in the market amid a fierce competition [1]. Biology functions as a main source of human inspiration and has even played a significant role in the development of early human inventions that can be traced back to a thousand years ago [2]. Nowadays, humans are facing severe threats to their survival, e.g., shortage in resources and serious environmental pollution. Biological wisdom is a key component of human sustainable development that has attracted an increasing amount of research attention. Previous studies have attempted to develop biologically inspired innovative solutions, and biological wisdom has subsequently become an important branch in the field of design methodology. With the emergence of advanced technologies such as electric microscopes and sophisticated gene engineering methods, scientists can easily observe and uncover principles from biological phenomena that can encourage biologically inspired innovations.

The notion of bionics was introduced in the 1960s [3] and has since then become an independent discipline. After half a century of development, various terminologies and methodologies have emerged to guide designers in applying biological knowledge efficiently in engineering design. These methodologies involve various types of knowledge from different abstraction layers, namely, strategy, behavior, physiology, and morphology [4]. These types of knowledge function as prototypes and wisdoms that inspire the development of artificial products that aim not only to fulfill design requirements but also to achieve goals in energy saving and sustainable development [5]. These design solutions can be found especially in the domains of energy saving [6] and artificial intelligence [7].

Biologically inspired methods come in various forms yet are built on the same purpose, that is, to explore the potential application of biological knowledge in engineering design. On the one hand, these methods help engineering users choose the most appropriate way of finding the best solutions to their design problems. On the other hand, a global review of biologically inspired products can help researchers gain an overall vision of the topics relevant to the field and locate opportunities for launching new developments in unexplored regions.

This paper is organized as follows. First, the relevant terminologies and methodologies for biologically inspired design (BID) are presented in Section 2. The implementation of various aspects of biologically inspired innovations is summarized

in Section 3. The key technologies that support biologically inspired product innovation are sorted and investigated in depth in Section 4. The future development of BID is discussed in Section 5. The concluding remarks are presented in Section 6.

## 2 Terminologies and frameworks

Biological knowledge has a huge potential to inspire designers in finding creative solutions to their design problems. A systemic and creative BID method aims not only to extract innovative wisdoms from biological prototypes but also to integrate these wisdoms into various technological domains to create a new product or system. The following part summarizes the currently popular terminologies as well as their frameworks and main characteristics.

### 2.1 Biomimetics and biomimicry

Biomimetics and biomimicry are both perceived to be synonymous to bionics [8]. Proposed by Schmit [9], biomimetics refers to the imitation of biology to produce creative solutions based on the analogy of biological phenomenon [10]. This notion is not limited to natural imitation and has been expanded to include creative processes that are driven by biological observations [11,12]. Biomimetics can be mainly divided into construction biomimetics, processing biomimetics, and information biomimetics, and each of these subsets can be further subdivided. Specifically, construction biomimetics can be subdivided into biomimetics on materials, substances, prosthodontics, and robotics; processing biomimetics can be subdivided into biomimetics on energy, architecture sensors, and kinematics; and information biomimetics can be subdivided into neuron-bionics, evolutionary bionics, process bionics, and organizational bionics [13].

Compared with biomimetics, biomimicry focuses more on the sustainable wisdoms inspired by biological knowledge [14]. Biomimicry can be divided into the organ or tissue, behavioral, and ecosystem levels, and each of these levels can be further subdivided into the pattern, material, structure, process, and function dimensions [15]. Figure 1 shows the hierarchies of biomimetics and biomimicry to clearly distinguish these concepts.

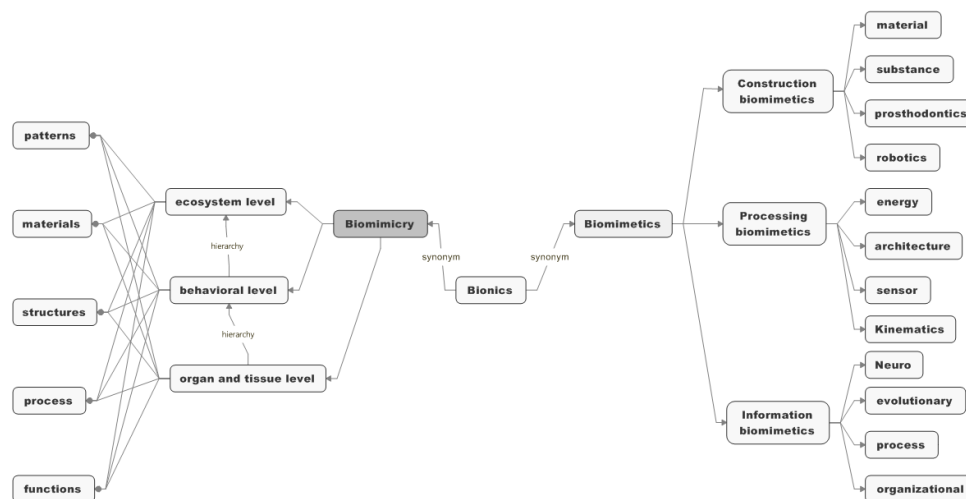


Fig. 1 Hierarchies of biomimetics and biomimicry

Both biomimetics and biomimicry inherit and expand the notion of bionics as well as manifest the importance of learning and imitating biology to engineering design. More importantly, these ideas have significantly expanded the area in which biological knowledge can be used to inspire innovation.

### 2.2 Framework of biologically inspired design

BID uses the analogies of biological systems to develop solutions to engineering and design problems [6]. BID can obviously improve the sustainability of the design results [16] and inspire breakthrough innovation ideas [17] that can be further developed into new patents [18]. As its most notable characteristic, BID allows for a cross-domain knowledge mapping to bridge the differences among several disciplines. The design results inspired by BID are not merely biological imitations but are relatively complete at the systematic level and can fulfill multiple function requirements even though the materials and substances used in BID to implement functions significantly differ from the engineering design [6].

The BID framework is formulated by three elements, namely, the biological representing methods that standardize biological knowledge as engineering-user-friendly forms, a database with a large amount of biological cases that serves as a source of inspiration for BID (e.g., Asknature [19], an open web-based biological knowledge pool with around 1500 biological prototypes classified by function), and a design workflow that is expressed in a step-by-step form to facilitate a highly efficient BID design.

Built on the same purposes of biomimetics and biomimicry, BID also embodies the idea that a design is inspired by biology. However, BID goes much deeper than both biomimetics and biomimicry by investigating the underlying mechanisms and presenting a systemic workflow that is formulated by various methods, tools, and processes for practical use even in complex design tasks.

## 2.3 BioTRIZ

BioTRIZ [20], which is developed by combining the basic principles in biomimetics and in theory of invention problem solving (TRIZ) [21], applies biological wisdom to solve problems in engineering design. Unlike other methods in bionics, BioTRIZ is built on contradiction ideas theory from TRIZ, which extracts innovative knowledge from patents in various backgrounds and standardizes such knowledge as invention principles [22]. BioTRIZ then inputs biological principles into the modernized rules of inventive problem solving (PRIZM) matrix. Those principles are applied by biology to resolve the contradictions [23]. In this matrix, all biologically inspired invention problems are standardized as contradictions between two out of six possible parameters, including substance, structure, space, time, energy, and information; feasible invention principles that can resolve these contradictions are also provided. Unlike the traditional TRIZ contradiction matrix that includes wisdoms extracted from engineering patents, BioTRIZ identifies the truth from those contradictions resolved by biological wisdoms through the strategies in structures and information rather than through energy approaches, which are usually applied in solving technical contradictions [20].

The algorithm in BioTRIZ can be divided into six stages, and each stage can be defined by using relevant TRIZ tools [23,24]. In Stage 1, the algorithm defines the main function requirement of the device in a standard TRIZ form. In Stage 2, the algorithm prepares a list of parameters relating to the main function requirements. In Stage 3, the algorithm searches for the appropriate biological prototype to meet a set of design goals. In Stage 4, the algorithm analyzes the behavior of bio-prototypes and defines their required attributes. In Stage 5, the algorithm arranges the parameters that are relevant to the main function. In Stage 6, the algorithm finds a combination of affordable parameters for a biomimetics device. BioTRIZ also has four design axioms, namely, axiom of simplification, axiom of interpretation, axiom of ideal result, and axiom of contradiction [24], which are usually applied in conjunction with the algorithm.

BioTRIZ attempts to reveal and use biological wisdoms on a higher abstraction level compared with biomimetics, biomimicry, and BID. This method expands the scope of TRIZ by proposing a series of design axioms and algorithms.

## 2.4 Theory of biological coupling

Based on long-term practices in bionics, researchers have proposed the notion of biological coupling to reveal the nature of a biological function. This notion defines biological function as a result of the organic combination of several mutual interdependent factors through a special coupling mechanism [25–27], which also serves as the foundation that makes a biological function work [28]. Based on the idea of biological coupling, a new bionics theory can be formulated to support multiple bionics, i.e., to fulfill a series of function requirements during a single biologically inspired design task.

Biological coupling can be divided into three sub-sections. Terminology and characteristics analysis serves as the foundation for the whole framework; the mechanism of biological coupling reveals the nature of biological functions and characteristics with the necessary process and control to formulate a systematic scientific expression of biological coupling [28,29]; and multi-bionics [21,27], which has been described as an important trend in the future development of bionics, applies six rules to implement the function in biological coupling.

Biological coupling theory is the first to define biological coupling as the nature of biological functions that can be used as a scientific method to support multi-bionics. This theory can be treated as a scientific finding than a design method for examining how to use and interpret biological coupling in practical engineering design.

## 2.5 Biological effects and multi-biological effects

The idea of biological effects was developed by extending the notion of “effect” in TRIZ to make biological principles feasible in solving engineering design problems [30]. As a result, biological effects have turned biological principles into a special form of knowledge that is compatible with TRIZ. Multi-biological effects (MBE) is an extensive version of biological effects that integrates biological coupling to meet multiple function requirements during a single task [31].

The MBE framework is divided into the following sections: The MBE knowledge representing method [32] is a diagrammatic model that expresses the biological elements and their causal relationships in biological prototypes; the MBE data structure [33,34] provides a large amount of sources of inspiration for the technical implementation of the MBE framework through biology-engineering analogy [35]; the MBE knowledge transfer facilitates the application of biological knowledge in solving technological problems and uses feature vectors to make the technical interpretation process applicable to design tasks [31]; and the biological-knowledge-driven integration of MBE into other innovative design methods in specific forms of design workflows [36].

As an innovation tool that inherits the merits of TRIZ and biological coupling, MBE implements biological knowledge in engineering design by using engineering-designer-friendly methods and tools [37]. Given its close relationship with TRIZ, MBE requires its users to have basic knowledge and skills in both conceptual design and TRIZ.

## 2.6 Genealogy of BID terminologies

Figure 2 illustrates the differences among several biologically inspired methods in terms of their abstraction levels and dates of creation. Among these methods, bionics is the earliest proposed notion with the most extensive range and the highest abstraction level. This notion is closely followed by biomimetics, which is the second earliest proposed notion yet has a more concrete meaning than bionics. Biomimicry places third in terms of creation date and has more detailed biological information than biomimetics, while BioTRIZ is a hybrid of biomimetics and TRIZ and has more abstract contents than BID. Biological coupling, despite being introduced later than others, has a higher abstraction level. Biological effects and MBE are recently proposed methods with sub-notions from TRIZ and are more concrete than BioTRIZ, with MBE being more specific than biological effects.

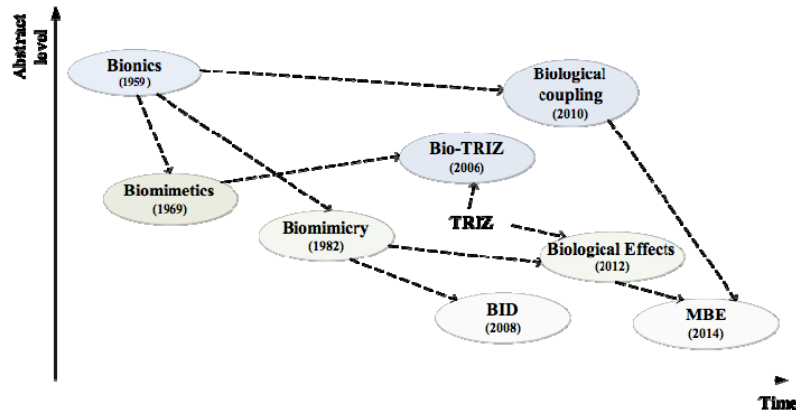


Fig. 2 The genealogy diagram of the terminologies in BID

## 3 Applications of biological knowledge in engineering innovation

After many years of development, biologically inspired innovation has been widely applied in both engineering and design domains and has yielded fruitful outcomes. According to the leverage method in biomimicry [14], the results of bionics design can be divided into three types based on biological hierarchies, i.e., the organ level, behavior level, and ecosystem level. From the perspective of engineering design, this paper classifies the extant approaches in bionics into three types, namely, technical copying of biological attributes, artificial simulation of biological function, and product or system design based on biological prototypes.

### 3.1 Technical copying of biological attributes

Copying biological features is the most widely used approach in bionics that can be traced back to the stone age where our ancestors replicated the shape of sharp animal teeth to create daggers and arrowheads. A new type of biomimetics drill was recently developed based on the mechanism of a wood wasp ovipositor [38], a high-efficiency PAX fan was developed by imitating the shape of a shell spiral [39], and a painless syringe was designed based on the parts of a mosquito's mouth [40]. All these innovations are products of copying biological features. Apart from biological shape, two other biological attributes can also be copied, such as color biomimetics, e.g., bionics camouflage [41], and morphological bionics, e.g., car designs inspired by wings of seagulls [42] and peacock-inspired chair designs [43].

In the technological domain, copying biological attributes is the most direct approach to biomimetics, where the product design focuses on clear biological features. Therefore, the biological prototypes must be investigated before engaging in biomimetics. To facilitate the copying of biological attributes, biological prototypes with a high level of granularity and advanced material molding techniques are required. In general, engineering innovations have a relatively short product development cycle.

### 3.2 Artificial simulation of biological functions

The artificial simulation of biological functions involves mimicking certain biological behavior by using technical methods. Based on the principle of biological coupling, biological functions are the results of combining multiple mutually interacting factors. Take for example the bionic super hydrophobic coating that mimics the function of a lotus leaf. This coating not only copies the microstructure of the lotus leaf surface [43] but also redesigns appropriate technical structures to imitate the substance secretion mechanism of the leaf and the other factors that are correlated with the main function.

Following the development of biological observation and analysis techniques, the number of innovations resulting from the simulation of biological functions has increased. These innovations typically include abrasion-resistant artificial materials based on the biological microscopic properties of unsmooth surfaces [44,45], new materials and shape designs that complete flapping-wing aircrafts as inspired by the flight mechanism of dragonflies [46,47], and a renovated agricultural apparatus design that can conserve energy and reduce resistance in soil digging [48] as inspired by the anti-sticking mechanism of soil creatures, such as dung beetles [49], pangolins [50], and earthworms [51].



The artificial simulation of biological functions is more complex than the technical copying of biological attributes. To facilitate the design process, a behavior model that can represent the biological function must be built while analyzing the relationships among certain biological elements.

### 3.3 Product or system development based on biological prototypes

Given that the studies on biological knowledge have inspired the development of a new innovation mechanism, the innovation results of bionics are no longer limited to the copying of attributes or the artificial simulation of biological behaviors but have also expanded to design tasks with highly comprehensive requirements, such as building new products or systems based on biological prototypes.

As can be seen in the biologically inspired development of products, especially micro-machinery at the nano-level, the biological principles and wisdoms show a much better performance than traditional technologies [4]. These products include a self-service assembly machinery in micro scale that uses dry ice to facilitate alignment movement as inspired by the alignment mechanism of cells [52]; a micro machine that mixes and transports medicine by using a biologically ciliated structure [53]; and a series of machineries for assembling or disassembling devices as inspired by the mechanism of fallen leaves and fruits in the fall [54,55].

Apart from the design of micro scale machinery, some bionic algorithms have also been proposed for optimizing and solving engineering design problems by imitating biological wisdoms. These algorithms typically include the genetic algorithm [56,57], which is developed by genetic information elements [58], and the ant colony algorithm, which is inspired by the wisdom of ant colonies in path planning [59]. These algorithms can be seen as alternative techniques for applying biological knowledge in creating new artificial systems.

Biological knowledge can also be used to improve or renovate manufacturing systems. A biological manufacturing system [60,61] with highly dynamic characteristics and high adaptability is created based on the mechanisms used in material cycling, sustainability, and transmission of genetic information in the biosphere. A highly adaptive, intelligent, and real-time system called “biologically inspired manufacturing system” [62] has been recently developed based on the ultra-short feedback path in the biological nervous system and has the ability to respond rapidly to the changes occurring in a production process.

## 4 Key technologies in biologically inspired creative design

All biologically inspired innovation methods seem to share a common goal, i.e., to facilitate biologically inspired designs by resolving a series of challenges with the help of specific methods and tools provided in their methodologies. These methods are sorted as follows according to the sequence of their functions in facilitating biologically inspired designs:

- 1) Knowledge representing methods, which make biological knowledge more feasible and comprehensible to engineering designers, thereby allowing them to apply such knowledge to their designs;
- 2) Biological knowledge feature reorganization, which helps designers recognize the characteristics of biological knowledge and match them to corresponding engineering design problems;
- 3) Biological knowledge data structure, which usually takes the form of a systemic biological knowledge database and functions as an important source of inspiration for supporting creative engineering design;
- 4) Biological knowledge technological implementation, which transfers innovative knowledge from biological prototypes to an engineering design;
- 5) Biological-knowledge-inspired design workflow, which achieves biologically inspired innovation through a step-by-step approach and produces a final design solution by integrating all of the abovementioned key technologies.

### 4.1 Biological knowledge representing methods

The predominant goal of biological knowledge representing methods is to propose a standard format for processing biological knowledge. Engineering designers with limited background knowledge on biology can understand and apply these methods to generate creative ideas. Two types of methods are mainly used for representing biological knowledge: Term-based or textual methods, which describe biological knowledge by using a structural corpus, and diagrammatic methods, which use a set of symbols to represent the components and their relations in biological prototypes.

Textual methods represent biological knowledge in a certain format that is formulated by nouns, verbs, prepositions, and other affiliates to map the terminologies [63,64] between the biological and engineering domains. This method also bridges the differences between these two domains by using WordNet [65] and applies other synonym-based tools to correlate biological and engineering functions. The function description template is a typical textual representation format that describes biological functions by using combinations of various types of vocabularies [66]. As one of their obvious merits, term-based methods can clearly represent the key features and aspects of a function and structure in biological prototypes, thereby making this function and structure applicable for solving engineering design problems; these methods are often used in biological knowledge retrieval [67]. However, without enough context knowledge, the represented textual

information is vague, and engineering designers can only rely on the provided description to analyze the components and understand their causal relations in biological function.

Meanwhile, diagrammatic methods use vivid graphic elements to express the elements of structures, functions, behaviors, and their connections in biological systems. A large number of methods have been classified as diagrammatic, and some typical examples are described as follows.

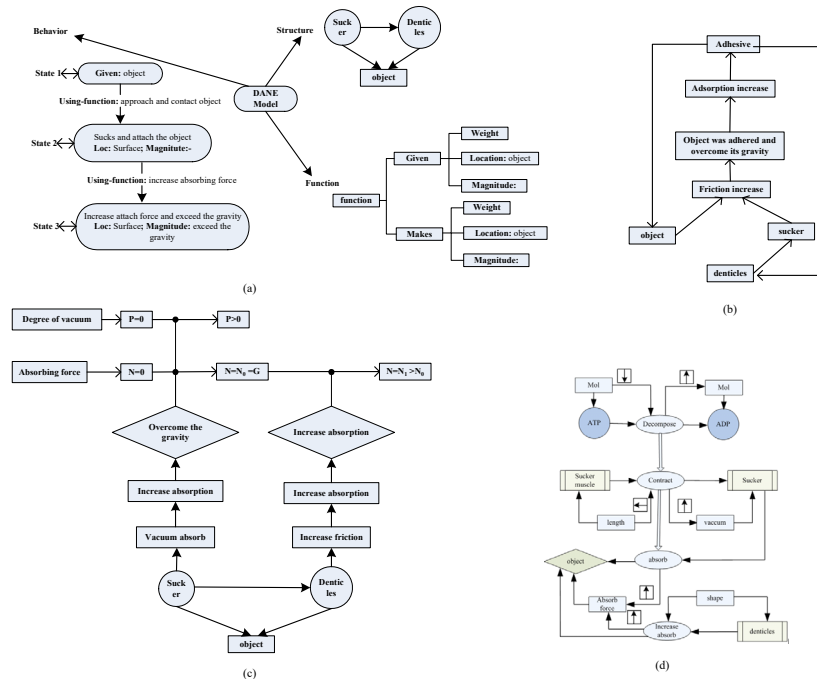
The design by analogy to the nature engine (DANE) [68] is based on the structure-behavior-function (SBF) model and represents the biological prototype from the aspects of structure, behavior, and function. This method has been proven useful in improving the usage efficiency of biological knowledge [68,69]. Similarly, bio-SBF is another biological knowledge process method based on the SBF model that can be seen as a variant of DANE [70].

State-action-parts-physics-input-organ-environment (SAPPhIRE) [71] dissects the causal relationships among various information components based on the changes in their physical state, but these knowledge elements are not limited to the physical level but may also include other types of knowledge, including the information on biological tissues and structure domains [71,72].

The united ontology BID (UNO-BID) model [73] was proposed with an aim to combine the DANE and SAPPhIRE models on the ontological level and to reflect the advantages of these models in representing biological knowledge.

The MBE modeling method [31–33] integrates the energy-material-signal model in engineering design [37] and the substance-field-analysis model in TRIZ [21]. In MBE, a behavior-level perspective is applied to reveal the characteristics of biological compositions, structures, attributes, and other aspects.

However, despite being built on the same ideas and principles, diagrammatic methods employ varying models. This paper uses the suckers on octopus tentacles as an example to clearly demonstrate such differences. The models of DANE, SAPPhIRE, UNO-BID, and MBE for this example are presented in Figs. 3(a)–3(d), respectively.



**Fig. 3** Various diagrammatic models for the structure of octopus suckers. (a) DANE; (b) SAPPhIRE; (c) UNO-BID; (d) MBE. ATP is the abbreviation of adenosine triphosphate, ADP is the abbreviation of adenosine diphosphate, Mol is the physical unit for mole

By using various graphic symbols, diagrammatic representation is more vivid and able to reveal more information compared with textual representation. In addition, the biological knowledge represented in diagrammatic form is very similar to product function models, which are being widely used by engineering designers. Therefore, diagrammatic methods can help inspire creative engineering designs. Although these methods do not require much background knowledge on biology from their users compared with textual methods, diagrammatic methods still have some specific requirements related to the capabilities of users in modeling and analyzing function designs.

## 4.2 Biological knowledge feature recognition

Feature recognition is important in revealing the potential use of biological knowledge in the engineering domain. For biological feature, recognition and analysis mainly depend on biological knowledge representing methods, which play a key role in organizing biological knowledge. Given the variety of biological knowledge representing methods, the methods for knowledge feature recognition also differ from one another. However, similar to biological knowledge representing methods, knowledge feature recognition methods can also be classified into two types.

By using textual methods, users can easily recognize the features of biological prototypes by reading and understanding their descriptions that are written by using standard terminologies, such as those included in the function basis [74] or the “engineering to biology thesaurus” [75,76], which is similar to function basis but is more specific to bionics, to effectively summarize the characteristics of biological knowledge.

For diagrammatic methods, in the DANE model, a specific terminology [77] formed by verbs, function carriers, objects, and auxiliary components is used to identify the characteristics in biological prototypes. Meanwhile, bio-SBF [71] uses the traditional function expression method, which combines verbs with nouns and uses certain variables and constraints to analyze biological characteristics. SAPPhIRE applies the similarity between artificial and biological systems in casual relationships to identify and analyze the characteristics in biological prototypes. UNO-BID replaces the traditional verbs and noun function description with the dynamic physical parameters of the system to recognize biological features for future use. MBE uses a terminology called general attribute operating [35] to extract innovative knowledge from biological prototypes. Compared with textual methods, diagrammatic methods need certain terms to identify the features of biological prototypes. The aforementioned benefits only emphasize the need to integrate these two key technologies.

### 4.3 Biological knowledge data structure construction

Studies on the data structure of biological knowledge are based on the identification and analysis of the aforementioned characteristics with an aim to classify various biological prototypes based on their functional features. By using the proposed structure, a large number of biological prototypes can find their appropriate places, and a biological knowledge database can be constructed to facilitate product innovation.

Asknature [19] is currently the most influential database for inspiring creative ideas. This database is built on taxonomy, a hierarchy function terminology set that sorts biological prototypes to make them available to engineering users when solving design problems.

BID has two types of databases. The functional keyword searchable repository includes biological functions and behavior characteristics based on a function index [78], while the BID cases repository contains biological prototypes and BID results that are inspired by the prototypes in pairs [79].

The natural system database in the software called IDEAINSPIRE [80] has approximately 100 biological entities that are built on the casual relations in SAPPhIRE to inspire engineering innovations.

MBE employs a specific coding method that uses the basic notions from “product genes” [81,82] to build a framework of the MBE knowledge database. The MBE coding method covers not only abstract information, such as the needs of customers, design constraints, and function requirements, but also concrete information, such as biological behaviors, mechanisms, and structures.

Despite showing variations in their concrete forms, the current biological knowledge data structures share a common goal, i.e., to use synonyms and hyponymy to match the biological knowledge for solving engineering problems. The principles in reverse engineering [83] and ontology [84] have been also applied in biological knowledge processing.

### 4.4 Biological knowledge technological implementation

Technological implementation refers to the formulation of practicable solutions to engineering design problems. However, the knowledge cross-domain analogy and usage create main obstacles in the transferring process [4].

In BioTRIZ, the biologically inspired design problems are reorganized and modified into typical TRIZ problems, such as technological contradictions; therefore, designers apply the invention principles in the PRIZM matrix and use other tools to generate creative solutions [85]. However, the biological knowledge in the form of invention principles is too abstract to be used effectively by ordinary engineering designers.

In BID, biological knowledge is applied in the technological context through biological analogy [86,87]. Biological knowledge is transformed into technological designs by using four approaches, namely, biological terms comprehension, biological escape, variable transformation, and analogical transformation. Given that analogy shows an excellent performance in the extraction and utilization of biological knowledge, several conceptual design processes have been proposed based on the idea of biological analogy. The core of biological analogy lies in dividing knowledge into appropriate abstraction levels in accordance to the types of design tasks [88].

Bio-SBF proposes the transfer-cluster-synthesis algorithm to cluster features from the functions, behaviors, structures, design constraints, and other aspects of the information for formulating technological solutions.

SAPPhIRE can show the biological knowledge in various abstraction levels in a single representing model that can support various kinds of biologically inspired analogies on different levels [89].

The technological implementation of MBE mainly depends on the similarity in the functions of the biological system and engineering products. The cluster algorithm is often used to calculate the degree of similarity among the functional characteristics, resources, and other kinds of information for setting the cluster goals. This algorithm is also applied to map

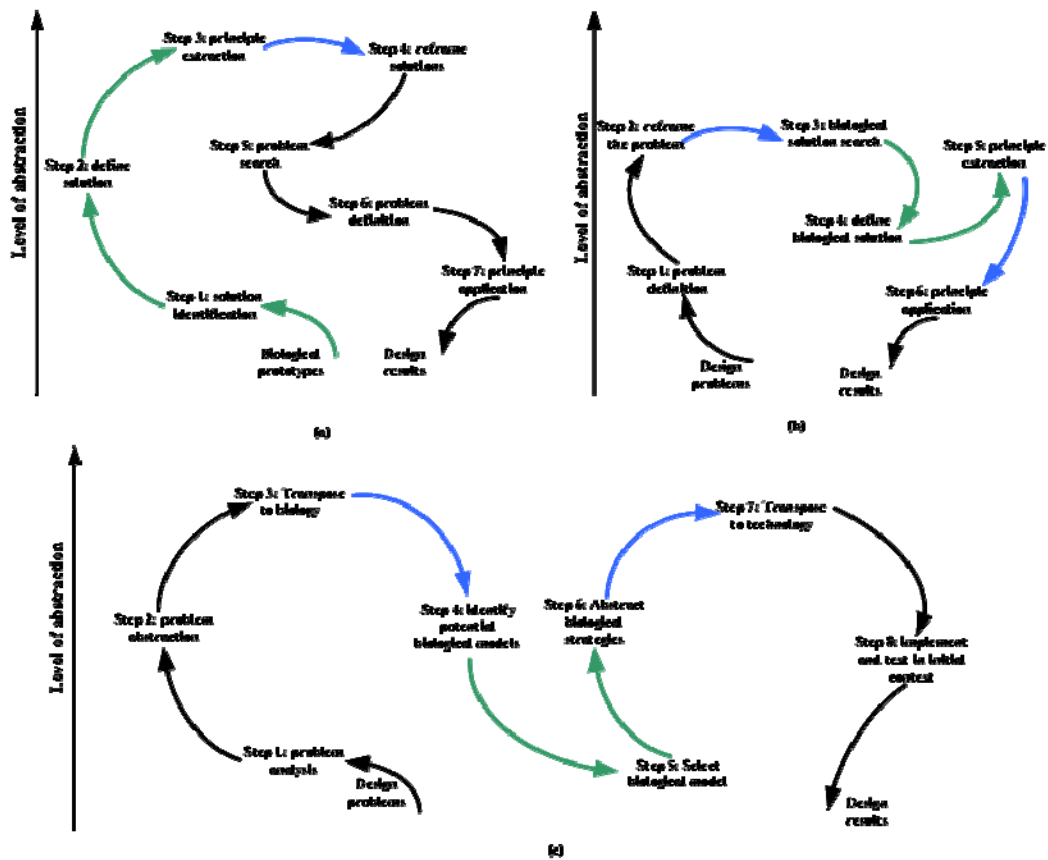


the function requirements in engineering design to the appropriate biological prototypes, biologically inspired parts, equipment, and products.

## 4.5 Design algorithms for biologically inspired innovation

The BID process is the integrated outcome of key technologies that follow a step-by-step workflow. This process can be classified into two types, namely, the solution-driven BID process and the problem-driven BID process, based on the differences in their starting point for solving design problems [6].

The solution-driven BID process includes seven steps from the formation of original biological principles to the production of engineering design results as shown in Fig. 4(a). Meanwhile, the problem-driven BID process is divided into six stages starting from the specification of the engineering design problem to the proposal of design solutions by applying biological principles as shown in Fig. 4(b). Compared with the solution-driven process, the problem-driven process is much more similar to the conceptual design process. With successive development [90], an eight-stage unified problem-driven biomimetics process is proposed to represent a highly systemic and practical BID process as discussed in Fig. 4(c). Table 1 lists each step of feasible unified problem-driven methods and the tools proposed in various bio-inspired innovation methodologies.



**Fig. 4** Typical design process in biologically inspired innovation. (a) Solution-driven process; (b) problem-driven BID process; (c) eight-stage unified problem-driven biomimetics process

**Table 1** Feasible methods that can be used in unified problem-driven biologically inspired innovation

Steps	Name	Feasible methods & tools
1	Problem analysis	Define the main function (BioTRIZ, MBE); define the problem (BID, DANE); describe the problem by using an adverb triplet (SAPPhIRE); specify the function terms (bio-SBF)
2	Abstractly define problems	Reframe the problem (BID, DANE); functional modeling (BID, MBE)
3	Transport to biology	Look for prototypes in biology (BioTRIZ); search for a biological solution (BID); translate the input into analogies (SAPPhIRE); search for relevant function terms (bio-SBF); general attribute operation (MBE)
4	Sort potential bio-prototypes	Biological database (DANE, SAPPhIRE, MBE); PRIZM matrix (BioTRIZ); knowledge cells library (bio-SBF)

5	Compare and select bio-prototypes	Frequent terms (DANE, SAPPPhIRE, bio-SBF); grey cluster (MBE)
6	Analyze biological strategies	Biological knowledge representing methods (DANE, ...)
7	Transport to technology	Biological analogies (BID, MBE, bio-SBF); invention principles (BioTRIZ); principle application (BID)
8	Implement & verify	Function design, grey cluster, and evaluation (MBE)

## 5 Future trends of biologically inspired creative design

Given its huge potential, biologically inspired innovation has developed from a method to support simple product designs to an approach for optimizing process planning and manufacturing strategies. The creative solutions driven by biological knowledge have surpassed the range of engineering products or process design, e.g., new bionic building materials inspired by corals have been developed [91], the microbial metabolic effect has been applied to bio-degrading pollutants [92], new bio-based energy sources have been created [93,94], and a new effective traffic control system that mimics the migration of ant colonies has been proposed [95]. All of these products enrich the achievements of human innovations that are inspired by biological knowledge. By observing its latest achievements, the development trend of biologically inspired innovation can be classified into systemic, integrated, and intelligent trends.

### 5.1 BID facing to systemically interdependent multiple design tasks

With the emergence of certain notions such as biological coupling, MBE, UNO-BID, and bio-SBF, biologically inspired innovation is undoubtedly capable of mimicking biological functions at the systemic level. Moreover, biological coupling has revealed the nature of biological functions and has manifested these functions in engineering design. Therefore, all coupled biological factors and their casual relations must be taken into consideration when developing biologically inspired engineering designs. SAPPPhIRE, UNO-BID, and MBE are useful models for analyzing the logical connections among different factors in biological prototypes and for ensuring their future application in developing systemic biologically inspired designs.

Multi-bionics is predicted to become a typical form of systemic biologically inspired innovation in which multiple interdependent design tasks are solved by technologically stimulating various features in a biological prototype. However, the current tools provided in BioTRIZ and BID are designed for single bionic design tasks and cannot sufficiently support multi-bionics. Therefore, a better approach that supports multi-bionics has become a hot topic in biologically inspired innovation research because of its potential in facilitating the development of methods and tools for multi-bionics in the future. The systemic technological realization of biological prototypes from the biological coupling perspective not only copies biological characteristics with obvious advantages but also uses the interrelations among coupled biological factors. These biological characteristics and factors result from natural wisdoms and can bring benefits to engineering designs. However, the advancements in effectively preserving and imitating the natural bonds in biological prototypes still have a long way to go, thereby underscoring the need to further study on multi-bionic-based methods. The development of these methods will enable us to analyze the characteristics of different biological species in a biota or even in an ecosystem to support the innovations at the strategic, methodological, and organizational levels.

### 5.2 The integration of BID and other innovation design methods

The transformation of knowledge from the biological domain to engineering design requires the use of traditional design methods and tools. As the systemic development of bionics continues to accelerate, the biologically inspired design process is becoming more complex. Therefore, integrating BID processes, methods, and tools in product conceptual design has also become necessary to improve design efficiency. Meanwhile, along with the increasing capacity and quality of the biological knowledge database, combining biological knowledge with other product design methods has become increasingly significant in creative design.

Integrating biological knowledge with other design methods has become an important development trend in the self-evolution of various biologically inspired innovation methods. Bio-TRIZ has integrated some principles of TRIZ to enhance its compatibility with contradictions and resources analysis and to facilitate the production of biologically inspired creative solutions.

DANE, SAPPPhIRE, UNO-BID, and bio-SBF can represent the characteristics of biological knowledge from the structural, behavioral, and systematic aspects as well as lay the foundation for integrating such knowledge with function design, reverse engineering, axiomatic design, and case reasoning design methods to yield innovation outcomes. MBE is a result of combining biological coupling ideas, while TRIZ, along with its knowledge representing models, can reveal the different aspects of knowledge in biological prototypes. Given that MBE has a natural bond with TRIZ and systemic engineering design, function combination, trimming, and other products of conceptual design methods are compatible with MBE. In the long run, MBE is expected to develop into a platform that integrates innovative knowledge, methods, and tools to generate biologically inspired creative ideas and solutions to engineering design problems. Based on the above discussions,

integrating biologically inspired innovation methods with other product design methods is an inevitable developing trend, and similar to systemic BID methods, such integration will become a future hot spot in the engineering design field.

### 5.3 Computer-aided biological inspired design innovation methods

The biological innovation knowledge database is predicted to expand continuously in the information era given the massive amount of inputted innovation information. Without applying computer-aided methods, engineering designers cannot address the information explosion or apply biological knowledge in engineering design. Computer-aided searching and matching methods can provide scientific measures to address the continuously growing amount of biological knowledge.

The development of intelligent biologically inspired innovation methods not only meets the requirements for processing massive amounts of biological information but also effective integrated design methods. To the best of our knowledge, the natural-language-analysis-based biological knowledge extraction method is a pioneer intelligent biologically inspired innovation method that uses both the biological knowledge database and the BID cases database as retrieval prototypes to solve practical design problems. Both the MBE coding method and parameters listed in bio-SBF are fundamental research topics in intelligent biological retrieval. The cluster algorithms used in MBE and bio-SBF as well as the biological analogies in BID all attempt to find intelligent strategies for matching biological knowledge with engineering design. Therefore, these aspects warrant further attention in future research on biologically inspired innovation methods.

Computer-aided decision making is a key component of biologically inspired innovation that is formulated by three aspects: Intelligent biological knowledge search to retrieve from the database some biological knowledge that can solve the dominating function in engineering problems; intelligent matching mechanism to map the biological knowledge with the targeted engineering problems especially in the systemic BID process that is highly complex and dependent on the intelligent matching algorithm; and an intelligent bio-inspired innovation software system to facilitate all stages of the design tasks by applying an intelligent decision-making service in different steps of the design process. Intelligent software is an ideal outcome of biologically inspired innovation methods. Therefore, the integration of relevant methodologies and intelligent knowledge searching and matching mechanisms warrants further research.

## 6 Conclusions

Biological knowledge is becoming a main source of inspiration for the biological-prototype-driven creative design of products that can revolutionize our daily life. In the near future, biological wisdoms may become the most important resource for solving urgent issues in environment, energy, and medicine, all of which are crucial to human survival. This paper reveals that the application of biological knowledge in engineering innovation practice has evolved from imitating simple biological characteristics to building new products, design processes, and new manufacturing systems. The implementation of biological knowledge continues to increase in depth to fulfill highly complex design tasks.

This paper has reviewed the characteristics and composition of several typical biologically inspired innovation methods and summarizes the known applications of biological knowledge in various design domains. This work also analyzes the key technologies being used in the process of biologically inspired innovation, which can be divided into five aspects: Biological knowledge representing, biological characteristics reorganization, biological knowledge data structure construction, biological technological implementing, and biologically inspired design algorithms. By analyzing the findings of previous research, this paper identifies three future development trends for biological inspired innovation, namely, systemic, integration, and intelligent.

**Acknowledgements** This paper was sponsored by the National Natural Science Foundation of China (Grant Nos. 51675159 and 51475137), the Natural Science Foundation of Hebei Province of China (Grant No. E2015202029), China Scholarship Council and Hebei in the Graduate Student Innovation Ability Training Project.

## References

1. Lu Y. Innovation Inspiration—Thinking About a Century's Technological Innovation. Beijing: Science Press, 2013 (in Chinese)
2. Benyus J M. Biomimicry: Innovation Inspired by Nature, New York: Harper Collins Publishers Inc, 2002
3. Sun J, Dai Z. Bionics today and tomorrow. *Acta Biophysica Sinica*, 2007, 32(2): 109–115 (in Chinese)
4. Shu L H, Ueda K, Chiu I, et al. Biologically inspired design. *CIRP Annals-Manufacturing Technology*, 2011, 60(2): 673–693 [doi:10.1016/j.cirp.2011.06.001](https://doi.org/10.1016/j.cirp.2011.06.001)
5. Pan Y. Heading toward artificial intelligence 2.0. *Engineering*, 2016, 2(4): 409–413 [doi:10.1016/J.ENG.2016.04.018](https://doi.org/10.1016/J.ENG.2016.04.018)
6. Helms M, Vattam S S, Goel A K. Biologically inspired design: Process and products. *Design Studies*, 2009, 30(5): 606–622 [doi:10.1016/j.destud.2009.04.003](https://doi.org/10.1016/j.destud.2009.04.003)
7. Pawlyn M. Biomimicry in Architecture. London: RIBA Publishing, 2011
8. Vincent J F. Biomimetics—A review. *Proceedings of the Institution of Mechanical Engineers. Part H, Journal of Engineering in Medicine*, 2009, 223(8): 919–939 [doi:10.1243/09544119JEIM561](https://doi.org/10.1243/09544119JEIM561)
9. Schmitt O H. Some Interesting and Useful Biomimetic Transforms, In: *Proceedings of the Third International Biophysics Congress*. Boston, 1969

10. Harkness J M. A lifetime of connections: Otto Herbert Schmitt, 1913–1998. *Physics in Perspective*, 2002, 4(4): 456–490 [doi:10.1007/s000160200005](https://doi.org/10.1007/s000160200005)
11. Von Gleich A, Pade C, Petschow U, et al. *Potentials and Trends in Biomimetics*. Berlin: Springer, 2010
12. Stokholm M D J. *Bionics*. Aalborg: Architecture. A&D Skriftserie 51. 2005
13. Reisen K, Teschemacher U, Niehues M, et al. Biomimetics in production organization—A literature study and framework. *Journal of Bionics Engineering*, 2016, 13(2): 200–212 [doi:10.1016/S1672-6529\(16\)60294-9](https://doi.org/10.1016/S1672-6529(16)60294-9)
14. Aziz M S, El sherif A Y. Biomimicry as an approach for bio-inspired structure with the aid of computation. *Alexandria Engineering Journal*, 2016, 55(1): 707–714 [doi:10.1016/j.aej.2015.10.015](https://doi.org/10.1016/j.aej.2015.10.015)
15. Zari M P. Biomimetic approaches to architectural design for increased sustainability. *Design*, 2007, 033
16. Anastas P T, Warner J C. *Green Chemistry: Theory and Practice*. London: Oxford University Press, 2000
17. Forbes P. *The Gecko's Foot: Bio-inspiration, Engineering New Materials from Nature*. New York: W. W. Norton & Company, 2005
18. Bonser R H C. Patented biologically-inspired technological innovations: A twenty year view. *Journal of Bionic Engineering*, 2006, 3(1): 39–41
19. Asknature. Biomimicry Taxonomy. 2017. Retrieved from <http://asknature.org/aof/browse>
20. Vincent J F V, Bogatyreva O A, Bogatyrev N R, et al. Biomimetics: Its practice and theory. *Journal of the Royal Society, Interface*, 2006, 3(9): 471–482 [doi:10.1098/rsif.2006.0127](https://doi.org/10.1098/rsif.2006.0127)
21. Altshuller G. *The Innovation Algorithm: TRIZ, Systematic Innovation and Technical Creativity*. Worcester: Technical Innovation Center Inc., 1999
22. Pahl A K, Vincent J F V. Using TRIZ-based evolution trends to integrate biology with engineering design. In: *Proceedings of TRIZ Conference*. St. Louis, 2002
23. Bogatyreva O A, Bogatyrev N R. Complexity in living and non-living systems. In: *Proceedings of International TRIZ Conference*. Philadelphia, 2003, 16
24. Bogatyrev N, Bogatyreva O. TRIZ-based algorithm for biomimetic design. *Procedia Engineering*, 2015, 131: 377–387 [doi:10.1016/j.proeng.2015.12.417](https://doi.org/10.1016/j.proeng.2015.12.417)
25. Ren L Q, Liang Y H. Biological couplings: Classification and characteristic rules. *Science in China Series E: Technological Sciences*, 2009, 52(10): 2791–2800 [doi:10.1007/s11431-009-0325-8](https://doi.org/10.1007/s11431-009-0325-8)
26. Zhang Y, Zhou C, Ren L. Biology coupling characteristics of mole crickets' soil-engaging components. *Journal of Bionics Engineering*, 2008, 5: 164–171 [doi:10.1016/S1672-6529\(08\)60089-X](https://doi.org/10.1016/S1672-6529(08)60089-X)
27. Liu E T. Systems biology, integrative biology, predictive biology. *Cell*, 2005, 121(4): 505–506 [doi:10.1016/j.cell.2005.04.021](https://doi.org/10.1016/j.cell.2005.04.021)
28. Ren L Q, Liang Y H. Biological couplings: Function, characteristics and implementation mode. *Science China. Technological Sciences*, 2010, 53(2): 379–387 [doi:10.1007/s11431-010-0043-2](https://doi.org/10.1007/s11431-010-0043-2)
29. Ren L, Liang Y. Biological coupling mechanism. *Journal of Jilin university*, 2011, 5: 1348–1357 (in Chinese).
30. Zhao H, Cao G, Liang T, et al. Study on conceptual design process based on the biological effects. *Machine Design & Research*, 2011, 27(Suppl): 105–110 (in Chinese)
31. Liu W, Cao G, Tan R, et al. Research on measures to technical realization of multi biological effects. *Journal of Mechanical Engineering*, 2016, 52(9): 129–140 (in Chinese)
32. Liu W, Cao G, Du C, et al. Systematic modeling method on biological information faced to engineering application. *Chinese Journal of Engineering Design*, 2015, 22(2): 106–114 (in Chinese)
33. Liu W, Cao G, Tan R, et al. Research on method for coding multi biological effects models. *Chinese Journal of Engineering Design*, 2014, 21(1): 1–6 (in Chinese).
34. Liu W; Hou X, Cao G, et al. Research on innovation driven by multi biological effects and transcription of innovative genes. In: *Proceedings of the 5th Advanced Design Concepts and Practice*. Hangzhou, 2015
35. Jia L, Liu W, Tan R, et al. Research on product conceptual design based on biological-technological characteristic analogy. *Chinese Journal of Engineering Design*, 2015, 22(4): 301–308 (in Chinese)
36. Liu W, Cao G, Guo D, et al. Research on rapid response design based on multiple bionic. *Chinese Journal of Engineering Design*, 2015, 22(1): 1–10 (in Chinese)
37. Pahl G, Beitz W, Feldhusen J, et al. *Engineering Design: A Systematic Approach*. Berlin: Springer, 2007
38. Gao Y, Ellery A, Jaddou M, et al. Planetary micro-penetrator concept study with biomimetic drill and sampler design. *IEEE Transactions on Aerospace and Electronic Systems*, 2007, 43(3): 875–885 [doi:10.1109/TAES.2007.4383580](https://doi.org/10.1109/TAES.2007.4383580)
39. Harman J. *The Shark's Paintbrush: Biomimicry and How Nature is Inspiring Innovation*. London: Nicholas Brealey Publishing, 2013
40. Oka K, Aoyagi S, Arai Y, et al. Fabrication of a micro needle for a trace blood test. *Sensors and Actuators. A, Physical*, 2002, 97–98: 478–485 [doi:10.1016/S0924-4247\(01\)00872-X](https://doi.org/10.1016/S0924-4247(01)00872-X)
41. Zhang Y, Wu W, Liu Z. Design of bionic camouflage pattern. *Computer Engineering*, 2009, 35(6): 35–37 (in Chinese)
42. Wei C. Bionics design in product form and its application. *Packing Engineering*, 2010, 31(8): 46–49 (in Chinese)
43. Liu K, Jiang L. Bio-inspired design of multiscale structures for function integration. *Nano Today*, 2011, 6(2): 155–175 [doi:10.1016/j.nantod.2011.02.002](https://doi.org/10.1016/j.nantod.2011.02.002)
44. Ren L, Xu D, Qiu X, et al. Research on wear-resistant composite with bionic unsmooth surface. *Transactions of The Chinese Society of Agricultural Engineering*, 2001, 17(3): 7–9 (in Chinese)



45. Ren L, Yang Z, Han Z. Non-smooth wearable surfaces of living creatures and their bionic application. *Transactions of The Chinese Society of Agricultural Engineering*, 2005, 36(7): 144–147 (in Chinese)
46. Song F, Xiao K W, Bai K, et al. Microstructure and nanomechanical properties of the wing membrane of dragonfly. *Materials Science and Engineering A*, 2007, 457(1–2): 254–260 [doi:10.1016/j.msea.2007.01.136](https://doi.org/10.1016/j.msea.2007.01.136)
47. Ren L Q, Li X J. Functional characteristics of dragonfly wings and its bionic investigation progress. *Science China. Technological Sciences*, 2013, 56(4): 884–897 [doi:10.1007/s11431-013-5158-9](https://doi.org/10.1007/s11431-013-5158-9)
48. Ren L. Advances in research on bionics ground degradation ground machine. *Science China. Technological Sciences*, 2008, 51: 1353–1364 (in Chinese)
49. Tong J, Sun J, Chen D, et al. Geometrical features and wettability of dung beetles and potential biomimetic engineering applications in tillage implements. *Soil & Tillage Research*, 2005, 80(1–2): 1–12 [doi:10.1016/j.still.2003.12.012](https://doi.org/10.1016/j.still.2003.12.012)
50. Xangxu C, Ning Z, Wang Y, et al. Constitution of pangolin scales and mechanism of reducing adhesion of solid to their cuticle. *Transactions of The Chinese Society of Agricultural Engineering*, 1990, 6(3): 15–22 (in Chinese)
51. Gu Y Q, Mou J G, Dai D S, et al. Characteristics on drag reduction of bionic jet surface based on earthworm's back orifice jet. *Acta Physica Sinica*, 2015, 64(2): 024701
52. Shu L H, Lenau T A, Hansen H N, et al. Biomimetics applied to centering in microassembly. *CIRP Annals-Manufacturing Technology*, 2003, 52(1): 101–104 [doi:10.1016/S0007-8506\(07\)60541-1](https://doi.org/10.1016/S0007-8506(07)60541-1)
53. Oh K, Chung J H, Devasia S, et al. Bio-mimetic silicone cilia for microfluidic manipulation. *Lab on a Chip*, 2009, 9(11): 1561–1566 [doi:10.1039/b817409a](https://doi.org/10.1039/b817409a)
54. Hacco E, Shu L H. Biomimetic concept generation applied to design for remanufacture. In: *Proceedings of ASME 2002 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. Volume 3: 7th Design for Manufacturing Conference*. Montreal: ASME, 2002, DETC2002/DFM-34177: 239–246 [doi:10.1115/DETC2002/DFM-34177](https://doi.org/10.1115/DETC2002/DFM-34177)
55. Shu L H, Hansen H N, Gegeckaitė A, et al. Case study in biomimetic design: handling and assembly of microparts. In: *Proceedings of ASME 2006 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. Volume 4a: 18th International Conference on Design Theory and Methodology*. Philadelphia: ASME, 2006, DETC2006-99398: 163–170 [doi:10.1115/DETC2006-99398](https://doi.org/10.1115/DETC2006-99398)
56. Xiong W, Zeng B. Studies on some bionic optimization algorithms. *Computer Technology and Development*, 2010, 20(3): 9–13 (in Chinese)
57. Li Z, Fu Y. Motion planning of a bio-inspired biped wall climbing robot stepping over obstacles based on genetic algorithm. *Robot*, 2012, 34(6): 751–757 (in Chinese)
58. Yu X, Ram B. Bio-inspired scheduling for dynamic job shops with flexible routing and sequence-dependent setups. *International Journal of Production Research*, 2006, 44(22): 4793–4813 [doi:10.1080/00207540600621094](https://doi.org/10.1080/00207540600621094)
59. Song D, Zhang J. Batch scheduling problem of hybrid flow shop based on ant colony algorithm. *Computer Integrated Manufacturing Systems*, 2013, 19(7): 1640–1647 (in Chinese)
60. Ueda K, Vaario J, Fujii N. Interactive manufacturing: Human aspects for biological manufacturing systems. *CIRP annals-Manufacturing technology*, 1998, 47(1): 389–392 [doi:10.1016/S0007-8506\(07\)62858-3](https://doi.org/10.1016/S0007-8506(07)62858-3)
61. Ueda K, Hatono I, Fujii N, et al. Reinforcement learning approaches to biological manufacturing systems. *CIRP Annals-Manufacturing Technology*, 2000, 49(1): 343–346 [doi:10.1016/S0007-8506\(07\)62960-6](https://doi.org/10.1016/S0007-8506(07)62960-6)
62. Tang D, Wang L, Gu W, et al. Modelling of bio-inspired manufacturing system. In: *Proceedings of the 6th CIRP-Sponsored International Conference on Digital Enterprise Technology*. Berlin: Springer, 2010, 1165–1174
63. Ke J, Wallace J S, Shu L H. Supporting biomimetic design through categorization of natural-language keyword-search results. In: *Proceedings of ASME 2009 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. Volume 8: 14th Design for Manufacturing and the Life Cycle Conference; 6th Symposium on International Design and Design Education; 21st International Conference on Design Theory and Methodology, Parts A and B*. San Diego: ASME, 2009, DETC2009-86681: 775–784 [doi:10.1115/DETC2009-86681](https://doi.org/10.1115/DETC2009-86681)
64. Cheong H, Chiu I, Shu L H, et al. Biologically meaningful keywords for functional terms of the functional basis. *Journal of Mechanical Design*, 2011, 133(2): 021007 [doi:10.1115/1.4003249](https://doi.org/10.1115/1.4003249)
65. WordNet 3.0. 2017. Retrieved from <http://wordnet.princeton.edu/>
66. Golden I J, Retrieval F B A A. Developing a repository of biologically inspired product concepts. Thesis for the Master's Degree. City of College Park: University of Maryland, 2005
67. Parvan M I, Miedl F, Lindemann U. Nature-inspired process model for concept selection and evaluation in engineering design. In: *Proceedings of the 9th NordDesign Conference*. Aalborg, 2012
68. Goel A K, Vattam S, Wiltgen B, et al. Cognitive, collaborative, conceptual and creative—Four characteristics of the next generation of knowledge-based CAD systems: A study in biologically inspired design. *Computer Aided Design*, 2012, 44(10): 879–900 [doi:10.1016/j.cad.2011.03.010](https://doi.org/10.1016/j.cad.2011.03.010)
69. Vattam S, Helms M, Goel A. Biologically inspired design: A macrocognitive account. In: *Proceedings of ASME 2010 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. Volume 5: 22nd International Conference on Design Theory and Methodology; Special Conference on Mechanical Vibration and Noise*. Montreal: ASME, 2010, DETC2010-28567: 129–138 [doi:10.1115/DETC2010-28567](https://doi.org/10.1115/DETC2010-28567)
70. Hu J, Ma J, Feng J, et al. An integrated transformation-clustering-synthesis algorithm to support intelligent biomimetic design. *5th Advanced Design Concepts and Practice*. Hangzhou, 2015
71. Chakrabarti A, Sarkar P, Leelavathamma B, et al. A functional representation for aiding biomimetic and artificial inspiration of new ideas. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 2005, 19(2): 113–132 [doi:10.1017/S0890060405050109](https://doi.org/10.1017/S0890060405050109)
72. Srinivasan V, Chakrabarti A, Lindemann U. *Towards an Ontology of Engineering Design Using SAPPPhIRE Model*. London: Springer, 2013, 17–26



73. Rosa F, Cascini G, Baldussu A. UNO-BID: Unified ontology for causal-function modeling in biologically inspired design. *International Journal of Design Creativity and Innovation*, 2015, 3(3-4): 177-210 [doi:10.1080/21650349.2014.941941](https://doi.org/10.1080/21650349.2014.941941)
74. Wood K L, Stone R J B, McAdams D R J, et al. A functional basis for engineering design. *Reconciling and Evolving Previous Efforts*, 2002, 13: 65-80
75. Nagel J K S, Nagel R L, Stone R B. Abstracting biology for engineering design. *International Journal of Design Engineering*, 2011, 4(1): 23-40 [doi:10.1504/IJDE.2011.041407](https://doi.org/10.1504/IJDE.2011.041407)
76. Nagel J K S, Stone R B, McAdams D A. An engineering-to-biology thesaurus for engineering design. In: *Proceedings of ASME 2010 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. Volume 5: 22nd International Conference on Design Theory and Methodology; Special Conference on Mechanical Vibration and Noise. Montreal: ASME, 2010, DETC2010-28233: 117-128 [doi:10.1115/DETC2010-28233](https://doi.org/10.1115/DETC2010-28233)
77. Design & Intelligence Laboratory-Georgia Tech. DANE 2.0 Users Guide. Atlanta: Center for Biologically Inspired Design-Georgia Institute of Technology, 2011
78. Vattam S S, Helms M E, Goel A K. A content account of creative analogies in biologically inspired design. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 2010, 24(4): 467-481 [doi:10.1017/S089006041000034X](https://doi.org/10.1017/S089006041000034X)
79. Nagel J K S, Nagel R L, Stone R B, et al. Function-based, biologically inspired concept generation. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 2010, 24(4): 521-535 [doi:10.1017/S0890060410000375](https://doi.org/10.1017/S0890060410000375)
80. Chakrabarti A, Sarkar P, Leelavathamma B, et al. A functional representation for aiding biomimetic and artificial inspiration of new ideas. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 2005, 19(2): 113-132 [doi:10.1017/S0890060405050109](https://doi.org/10.1017/S0890060405050109)
81. Feng P, Yong C, Shuai Z, et al. Product gene based conceptual design. *Journal of Mechanical Engineering*, 2002, 38(10): 1-6 (in Chinese) [doi:10.3901/JME.2002.10.001](https://doi.org/10.3901/JME.2002.10.001)
82. Wei L, Cao G, Tan R, et al. Variant design based on products genes and physical descriptions. *Computer Integrated Manufacturing Systems*, 2015, 21(2): 381-392 [doi:10.13196/j.cims.2015.02.010](https://doi.org/10.13196/j.cims.2015.02.010)
83. Wilson J O, Rosen D. Systematic reverse engineering of biological systems. In: *Proceedings of ASME 2007 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. Volume 3: 19th International Conference on Design Theory and Methodology; 1st International Conference on Micro- and Nanosystems; and 9th International Conference on Advanced Vehicle Tire Technologies, Parts A and B. Las Vegas: ASME, 2007, DETC2007/DTM-35395: 69-78 [doi:10.1115/DETC2007-35395](https://doi.org/10.1115/DETC2007-35395)
84. Wilson J, Chang P, Yim S, et al. Developing a bio-inspired design repository using ontologies. In: *Proceedings of ASME 2009 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. Volume 8: 14th Design for Manufacturing and the Life Cycle Conference; 6th Symposium on International Design and Design Education; 21st International Conference on Design Theory and Methodology, Parts A and B. San Diego: ASME, 2009, DETC2009-87272: 799-808 [doi:10.1115/DETC2009-87272](https://doi.org/10.1115/DETC2009-87272)
85. Craig S, Harrison D, Cripps A, et al. BioTRIZ suggests radiative cooling of buildings can be done passively by changing the structure of roof insulation to let longwave infrared pass. *Journal of Bionics Engineering*, 2008, 5(1): 55-66 [doi:10.1016/S1672-6529\(08\)60007-4](https://doi.org/10.1016/S1672-6529(08)60007-4)
86. Vattam S S, Helms M E, Goel A K. Compound analogical design: Interaction between problem decomposition and analogical transfer in biologically inspired design. *Design Computing and Cognition*, 2008, 8: 377-396 [doi:10.1007/978-1-4020-8728-8\\_20](https://doi.org/10.1007/978-1-4020-8728-8_20)
87. Vattam S, Wiltgen B, Helms M, et al. DANE: Fostering Creativity in and Through Biologically Inspired Design. London: Springer, 2011, 115-122
88. Yen J, Weissburg M. Perspectives on biologically inspired design: Introduction to the collected contributions. *Bioinspiration & Biomimetics*, 2007, 2(4): 1029-1031 [doi:10.1088/1748-3190/2/4/E01](https://doi.org/10.1088/1748-3190/2/4/E01)
89. Sartori J, Pal U, Chakrabarti A. A methodology for supporting "transfer" in biomimetic design. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, 2010, 24(4): 483-506 [doi:10.1017/S0890060410000351](https://doi.org/10.1017/S0890060410000351)
90. Fayemi P E, Wanick K, Zollfrank C, et al. Biomimetics: Process, tools and practice. *Bioinspiration & Biomimetics*, 2017, 12(1): 011002 [doi:10.1088/1748-3190/12/1/011002](https://doi.org/10.1088/1748-3190/12/1/011002)
91. Calera. The special form of calcium carbonate that Calera makes in its process also mimics or copies the form of calcium carbonate that marine organisms use to make their shells and other structures. 2017. Retrieved from <http://www.calera.com/site/beneficial-reuse-of-co2/science.html>
92. Moreau J W, Weber P K, Martin M C, et al. Extracellular proteins limit the dispersal of biogenic nanoparticles. *Science*, 2007, 316(5831): 1600-1603 [doi:10.1126/science.1141064](https://doi.org/10.1126/science.1141064)
93. Deheyn D D, Wilson N G. Bioluminescent signals spatially amplified by wavelength-specific diffusion through the shell of a marine snail. *Proceedings of the Royal Society of London B: Biological Sciences*, 2010, 278(1715): 2112-2121 [doi:10.1098/rspb.2010.2203](https://doi.org/10.1098/rspb.2010.2203)
94. Lurie-Luke E. Product and technology innovation: What can biomimicry inspire? *Biotechnology Advances*, 2014, 32(8): 1494-1505 [doi:10.1016/j.biotechadv.2014.10.002](https://doi.org/10.1016/j.biotechadv.2014.10.002)
95. Couzin I D, Franks N R. Self-organized lane formation and optimized traffic flow in army ants. *Proceedings of the Royal Society of London B: Biological Sciences*, 2003, 270(1511): 139-146 [doi:10.1098/rspb.2002.2210](https://doi.org/10.1098/rspb.2002.2210)