Knowl Inf Syst (2018) 57:287–309
https://doi.org/10.1007/s10115-018-1159-0

REGULAR PAPER

Bionic knowledge and information reuse methodology for uncertainty minimization in product design

Prabhat Kumar[1] · **Puneet Tandon**[1]

Received: 14 September 2016 / Accepted: 12 January 2018 / Published online: 23 January 2018

Abstract The design process involves multiple stages to provide the solution for an actual or perceived need. The process needs different information at different stages to generate the desired output, but most of the time, the information is uncertain. Information uncertainty almost always makes design decision critical. The present work aims to reduce this information uncertainty in product design by reusing previous design knowledge. Reusing an existing ontology is an obvious way to minimize information uncertainty, and consequently, it can shorten the manufacturing lead time. However, the existing techniques have a few gaps that are still unaddressed. To fill these gaps, a methodology based on bionic engineering is proposed in this work for the purpose of design reuse in product development. Here, for the representation and manipulation of the knowledge, bionic-based reasoning approach is used for the development of the new product with the help of bionic reverse engineering. The proposed methodology is validated by illustrating an example of shoe design suitable to maneuver ill-conditioned roads. This work would be useful to the design and manufacturing practitioner in product development and decision making.

Keywords Information · Knowledge · Bionic engineering · Database design · Indexing methods · Information retrieval · Knowledge reuse · Information uncertainty

1 Introduction

Design can be defined as a process to convert an idea into a marketable product or service, to satisfy customer needs. The design process involves many stages so as to meet an actual or perceived need. Each step in the design process requires the designer; to not only identify

---

✉ Puneet Tandon
ptandon@iiitdmj.ac.in; tandon_p@rediffmail.com

Prabhat Kumar
prabhat.kumar@iiitdmj.ac.in

[1] Mechanical Engineering Discipline, Pandit Dwarka Prasad Mishra Indian Institute of Information Technology, Design and Manufacturing, Jabalpur, Dumna Airport Road, Jabalpur 482 005, Madhya Pradesh, India

the available information that defines a particular sub-problem, but also to use the knowledge and skills, along with the available tools, to process the information into a state such that the solution to the sub-problem is available. Systematic management of product information is vital for manufacturing enterprises in this information era. Due to complexity of products, limitations of power of human brain to analyze, time constraint and intense competition in the global manufacturing environment, the designer utilizes the previous design information as design knowledge at appropriate stages. Application of already available design knowledge is an excellent way to shrink information uncertainty during product design. Design knowledge is the accumulation of the information obtained throughout the product life cycle such as product design specifications, product implementation instructions, manufacturing processes, product performance data, service instructions, end of life characteristics. More than 75% of design activities fall into the categories like design modification, variant design, or case-based design [1]. Reduction in product development time and cost is a crucial issue, which requires the ability to design a product rapidly and collaboratively in a static environment. Design reuse provides a possible mean to solve such problems by reusing past design knowledge. Nowadays, the concept of design reuse is accepted as a valid approach to design. A limited number of attempts have been made to formalize the elements that constitute design reuse [2]. In this work, design reuse is applied to support the design knowledge gained from bionic engineering (BE). The proposed methodology provides a bionic design knowledge reuse framework to minimize information uncertainty within minimum time, cost and resources.

Design based on BE follows the principles of biology to design a product. However, literature lacks formal bionic design guidelines. In this work, a formal bionic design guideline has been proposed for design reuse in engineering practice. The available bionic design methods are unable to propose optimal design solutions. Hence, in this work, a methodology called bionic reverse engineering is proposed to achieve design optimization. The remainder of this paper is structured as follows. Section 2 discusses relevant literature regarding design reuse followed by its scope and research gaps that exist in the context of product design. Section 3 discusses the proposed methodologies that are coupled with bionic design and design reuse for rapid and collaborative design, as well as minimizes information uncertainty. In Sect. 4, an example is presented and followed by information uncertainty mitigation. Finally, in Sect. 5, summary and conclusions along with guidelines for design reuse are being presented.

2 Literature review

Increased competition for better product (or system) functionality, quality, and cost along with shorter delivery time presents remarkable challenges for any product manufacturing enterprise. Design reuse facilitates achieving these goals, and thus, nowadays noteworthy work is being done in the area of design reuse. Further, it is also endorsed that the idea of design reuse is an accepted and valid approach for product design. The review presented here is carried out under ‘design reuse’ umbrella. Duffy et al. [3] had classified the work carried out in the field of design reuse in three categories, namely (a) indexing and information retrieval, (b) knowledge modeling and utilization, and (c) exploration and adaptation. Here, we present literature review under these three categories only.

Indexing involves structuring cross-references of knowledge that encapsulate the range of interest to enhance retrieval of related information. There are numerous ways to express the information, i.e., single information may be represented in different manners, in different contexts or needs, and linguistic habits, that is why, it is critical to index the information.

During review of literatures, it has been observed that the majority of time spent by designers and engineers on large-scale design projects was on getting, handling or conveying information rather than on traditional "design" exercises. Likewise, Court et al. [4] concluded that 50% of designers' time was focused on managing the information that stems from the engineering design process. Consequently, there are various approaches, which intend to support knowledge reuse by identifying effective and efficient methods of indexing and retrieving knowledge. DEDAL is a knowledge-based retrieval framework, which utilizes engineering design experience by providing an intelligent guide for browsing multimedia design documents [5]. However, Yang and Cutkosky [6] observed that the limitation of DEDAL is its high cost, in context of ease of use and support. In the first place, each descriptor and subject in a document must be indexed by hand, which requires both time and knowledge of the project. Second, hand indexed systems are difficult to be updated. Maintenance is critical for items that changes rapidly, such as design documents. Therefore, it is concluded that the efficiency of information retrieval mainly depends on three factors—representation, indexing, and similarity analysis of cases in the case library [7].

Another project, design process encoding and retrieval (DESPERADO) consists of experienced engineering, software and industrial designers in ongoing projects [8,9]. Peng [10] had reported that this project had developed a computer-based tool that supports innovative design by empowering the sensitive and timely reuse of design ideas and experience in highly innovative design environments. DESPERADO provides the processes of encoding and retrieving design information and elicits design rationale as the work progresses. RODEO (an acronym for reuse of design objects) was created after examining reuse of designed projects in CAD framework [11,12]. Early researches focused on the definition of a formal model to describe design objects, design processes, and requirement specifications by their properties (features). RODEO was developed to implement, test and evaluate this model. knowledge reuse and fusion/transformation (KRAFT) architecture supports the fusion of knowledge from several distributed heterogeneous sources [13]. The KRAFT project had been characterized as a generic agent-based architecture to support combination of knowledge in the form of constraints expressed against an object data model [14]. KRAFT used open and adaptable agent style in which knowledge sources, knowledge fusing entities and users are all represented by independent KRAFT agents. Argo, developed by the microelectronics and computer technology corporation, is an analogical reasoning system for solving design problems [15]. This approach was employed to determine generic design problems. It used an analogical reasoning approach to select the most similar experience relevant to the design problem. Agro experiences were stored as design solutions, design plans and inclinations.

Knowledge modeling and utilization is an important part of computational design reuse. Three categories of knowledge modeling that are developed till date are: case-based reasoning (CBR), model-based reasoning (MBR), and plan reuse (PR). CBR is an approach for problem solving and learning that has got a lot of attention during last few years. Issues regarding suitable selection of a comparable past case and reusing it in the new problem context are tackled by CBR and thus substitute specific knowledge acquired through prior experience. Aamodt and Plaza [16] had observed that CBR leads to incremental and continuous learning. A new design experience is gained each time a problem is solved, thus, making the solution accessible for next set of problems. CASECAD is a case-browsing tool, which facilitates users to navigate through its memory to look at information that seems appropriate for the current interests [17]. In CASECAD, relevant information of the cases is represented using a variety of multimedia formats using natural language expressions of certain aspects and drawings to represent the physical appearance of a design [18]. A large computer-based library of architecture design is built in ARCAD [19]. It can support huge collections and improve designer decision making in complex tasks. Lee et al. [20] presented dynamic data interchange scheme (DDIS) for supporting data integrity between relational database module (RDM) and knowledge storage module (KSM), thereby accelerating the product development process in which every functional entity of a company is involved. DDIS automatically searches for similar cases in past design solutions, which are applicable to new problems.

MBR uses working models associated with real-world observations to draw conclusions. MBR type of knowledge is quite different than the CBR. MBR represents knowledge in general, whereas CBR represents case specific knowledge. The creation of MBR model is time-consuming, as it is necessary to make the model deep, complex, and detailed to achieve the best outcomes. Once MBR working model has been created, it may also require periodic updates. IDEAL used analogical reasoning to compare and reuse generalized knowledge rather than particular cases across different domains [21]. Duffy et al. [22] worked on a numerical and object based modeling system for conceptual engineering design. Their work was focused around an experimental framework NODES which was created to model knowledge of design objects and their related numerical relations. NODES provide knowledge modeling and design analysis support during the synthesis and modification of a design solution.

Plan reuse (PR) includes not only the storage of the rationale behind design decisions but also the replaying the appropriate design history during the new design activity. PR supports designer during the series of decisions and consequently generates new design solutions. Some popular approaches of PR are: VEXED, reconstructive derivational analogy (RDA), PERSPECT, SPIDA, etc.

The third category under design reuse, exploration and adaptation converts an abstract set of requirements into a definition of a physically realizable system and its adaptation, which is nothing but the extension of the utility (service) of products. According to Gu et al. [23], two classes of adaptabilities exist, i.e., product adaptability and design adaptability. Two types of design adaptations are also identified which include specific adaptability and general adaptability. Specific adaptability means the adaptation requirements are known during design stage. General adaptability of a product design means that the design in general is more adaptable to accomplish adaptation requirements than specific adaptability. Nowadays, a number of approaches have been developed by researchers in an attempt to achieve some form of knowledge exploration and adaptation. CADSYN and CASECAD knowledge representation is achieved by decomposing cases into subparts making the reuse of cases more flexible and efficient by eliminating irrelevant information. In this system, retrieval method is user-directed browsing and navigation attribute-value matching. For the assembly sequence and configuration design, COMPOSER approach represents design experiences in design cases. In this approach, variables, constraints and solutions are stored as attribute-value pairs and for retrieval, similarity matrices are employed. Zhang [24] proposed “DENOTE” that includes design knowledge modeling, and management of design knowledge evolutions. In DENOTE, libraries of previous designs are structured according to four particular concepts and their inter-relationships, namely function, mode of operation, solution and part. Gozali [25] classified various approaches on the basis of application domain, retrieval methods and adaptation such as Archie, Archie-II for architecture, AskJef for software, Composer for assembly sequence and configuration design, Repro for chemical process, Panda for Fire engines, Kritik for physical devices, etc.

The product design process requires different information at various stages of its process. It is too complicated for precise description; thus, there is a need not only to understand uncertainty in the process but also to trace it into a reasonable model. Ascough et al. [26] defined uncertainty as limited information about a specific area. Walker et al. [27] defined uncertainty as any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system. Sigel et al. [28] defined uncertainty as the absence of confidence in knowledge related to a specific design problem. Similarly, Chowdhury et at. [29] considered uncertainty that is closely related to the information need, and it is argued that uncertainty reduces as the information seeking process proceeds, till the end of the process. These descriptions indicate uncertainty is an information or knowledge gap and can be handled through proper identifications of required information.

2.1 Research gap

Reusing existing design knowledge in a design problem is a technique to reduce information uncertainty along with minimization of efforts, risks and cost. However, for reusing the existing design effectively, designer needs to handle the lacunae in the existing approaches, some of which are listed below:

1. The problem with design reuse in engineering practice is lack of any formal guideline or approach to help encourage its application and thereby allow designers to effectively benefit from previous domain knowledge [3].
2. Traditional information retrieval has indexing and retrieval problems [30]. In product design, the complication of knowledge presentation and the scattered distribution of knowledge resources make knowledge sharing and reuse difficult [31]. As a consequence, it was argued that designer would increasingly rely on retrieving the stored information, independent of human memory. It was concluded that more research is needed to understand how to capture large and integrated information spaces.
3. Previous empirical studies focus on the reuse of geometric modeling and do not consider other issues for the design process, such as engineering analysis, optimization [32] and mass customization [33] in detail. Therefore, the current design reuse systems need additional study.

2.2 Motivation

The design process can be defined as a series of tasks that utilize scientific principles, technical information and creativity so as to produce a solution to meet an actual or perceived need. Consequently, nowadays product design is very knowledge intensive. In order to stay competitive, engineering companies need to react quickly to engineering change (EC) requests that may crop during any phase of a product's design [34]. Design reuse is capable of capturing technical information, reducing development costs and manufacturing lead time in a competitive market [35]. Therefore, reuse of existing information and knowledge for new purposes is an essential aspect of effective product design. Applying an existing design information and knowledge helps to avoid some of the resources consumed in original design and analysis. It also helps to avoid the error and uncertainty that accompanies all human activities [29,36]. Many reviews concluded that design for reuse can provide the greatest benefits to the product development process when considering matrices such as time, cost, quality and performance.

3 Methodology

To fill the research gap for systematic exchanging, synchronization and reusing of information, this work combines bionic engineering with design reuse model. The major two phases that comprise this work are:

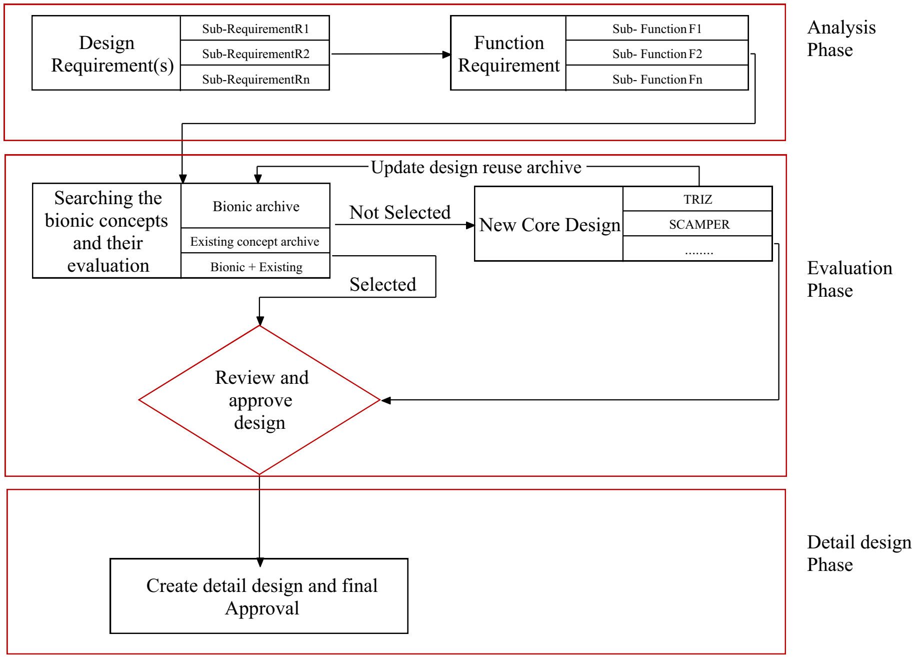


Fig. 1 Design methodology integrated with bionic design

Phase 1: Applications of bionic design

This stage presents some illustrations of bionic engineering, i.e., how nature or biological artifacts provide necessary information and functional solutions. Thereafter, a seven-step normative process is proposed to reuse design information prevalent in nature, or inspired by biology.

Phase 2: Integration of design reuse and bionic archive

This phase integrates bionic archive obtained after Phase I, with Duffy and Ferns [21] model and proposes an improvised model. Thereafter, mitigation of information uncertainty is presented.

3.1 Bionic design

Nature is the best school for scientists and engineers. Multiscale biological structures ranging from nano- to macroscale characterize materials, which play important roles in achieving structural and functional integrity in design. As per Jin et al. [37], the biological solutions provide inspiration to scientists and engineers to design multifunctional artificial materials with multiscale structures. Wen et al. [38] claimed that nature is an information sourcebook of behavior, function, color and shape, which can inspire visual designs and inventions. Studying the form and functional characteristics of a natural object can provide inspiration and information to product designers and help to improve the marketability of the manufactured products. Therefore, this work utilizes bionic designs for design reuse as shown in Fig. 1.

The database created for indexing and retrieval, named bionic database, is indexed by a set of keywords generated from biological forms, structures, constructions, functionality and general aesthetic appearance of bionic artifact, as shown in Table 1. The table exemplifies

Table 1 Natural objects and functional characteristics for engineering design

Natural objects	Functions (indexing)	References
Butterfly wings	Super hydrophobicity, directional adhesion, structural color, self-cleaning, chemical sensing capability, fluorescence emission functions	[39–41]
Lotus	Surfaces with roughness, induced super hydrophobicity, self-cleaning, and low adhesion	[42,43]
Polar bear fur	Optical property, high thermal insulation	[43,44]
Birds wings	Aerodynamics	[42]
Biological tissues	Self-healing	[42]
Bones	Excellent mechanical strength, self-damage repair	[45]
Fish scale	Superoleophobic and low adhesive	[46]
Peacock feather	Submicron structure and optical interference, reflection properties	[47]
Spider capture silk	Combination of strength and elasticity	[48,49]

the form and functional characteristics of a natural object and may serve as models for many applications in product designs.

Bionic-inspired designs use analogies to develop conceptual solutions of the problems. Many researches have been carried out in this area, and one can find many examples of this type. One of the popular processes in the area of nature-inspired design is biomimicry. Biomimicry induces concepts from nature for optimal design and construction of buildings, consumer goods and technology. Biomimicry is an innovative method that seeks sustainable solutions by emulating nature's time-tested patterns and strategies, e.g., a solar cell inspired by a leaf. Biomimicry-inspired innovations can create products and processes that are not only sustainable and efficient but also save energy, reduce material requirements, eliminate waste, increase and redefine product categories, drive revenue, etc. [50]. A few among the many biomimicry-inspired artifacts are presented below:

1. Nose is an inspiration to make an object perform multiple functions (e.g., filtering the air that is breathed in, acting as a sensory organ), apart from the primary function for which it is designed, and in the process eliminates the need of other parts. Hence, the nose is an inspiration of multifunctionality.
2. Hibiscus flowering plants change the color according to temperature range. Therefore, hibiscus is a genus of flowering plants, which inspires designs to improve the observability of things that are difficult to distinguish, by using colored additives or luminescent elements.
3. Segmentation of an object into independent parts, e.g., as inspired by orange and similar entities, so as to make an object easy to assemble or disassemble.
4. Egg inspires to place one object inside another (multiple layer, e.g., eggshell, outer membrane, inner membrane, chalaza, exterior albumen, middle albumen, vitelline membrane) and thus the inspiration for stacking of objects.

From above examples, bionic artifacts like orange for the balance segmentation, nose for multifunctionality, egg for stacking or cascading and hibiscus for observability, can be indexed. The indexing of bionic artifacts makes the retraction of design knowledge easy for the designer in future. To render the bionic design reuse process and to show forth knowledge indexing

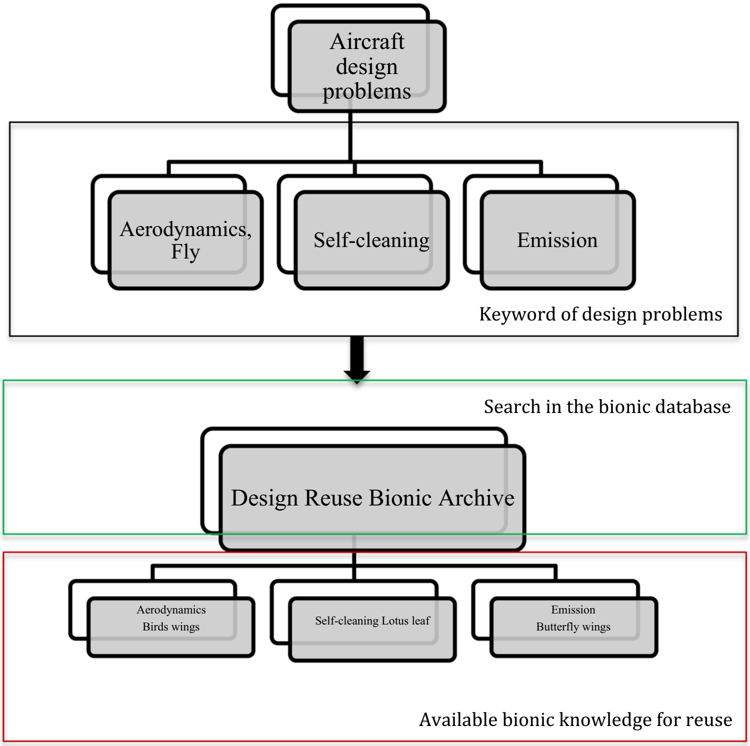


Fig. 2 Bionic design information retrieval for aircraft design

and abstraction, an example of aircraft design is presented with the help of Fig. 2. Some of the typical design challenges that require knowledge to solve them are:

- To fly and carry the weight of the people and cargo, the aircraft wings should be aerodynamically designed for easy flying
- To avoid the contaminants and improve the hygiene during flying, the aircraft should preferably have self-cleaning mechanism
- To provide the aircraft's position in low-visibility conditions, and to assist the ground control staff/other pilots, there should be emission of navigational signals

As per the literature, many information retrieval algorithms are available to improve retrieval performance. Keyword search is one of the most popular and well-accepted ways to retrieve needful information [51]. Zhang et al. [52] presented a framework for patent retrieval, where a list of relevant patent documents could be retrieved based on the generated queries. Inspired from their work, "relevance" is the key component in the proposed model for information extraction. Relevance factor measures the information quality, i.e., whether the available information addresses the existing design problem or not. In this work, the information can be abstracted based on (i) "relationship extraction," in the form of identification of relations between the design problems and bionic and (ii) "terminology extraction," to finding the relevant terms for a given corpus. Therefore, this work applied a multidimensional binary search algorithm [53] for the keyword search and information retrieval.

Table 2 Relations between Keywords and Index Knowledge

Knowledge Id	Attribute	Attributes value/ domain	Entity	References
BEK0001	Super hydrophobicity	aquaphobic (adj.) water-repellent (adj.) waterproof (adj.)	Butterfly wings	[39–41]
	directional adhesion	Adherence (noun.) Fidelity (noun) Stickiness (noun)		
	structural color	constitutional color (adj.) morphological color (adj.) skeletal color (adj.)		
	self-cleaning	self-purifying (adj. verb) cathartic (adj.) sweeping (noun. and verb)		
	chemical sensing capability	organic perceiving (verb) chemical detection (noun)		
	fluorescence emission functions	radiance (noun) luminescence (noun) illumination (noun)		
BEK0002	Surfaces with roughness	harshness irregularity	Lotus	[42,43]
	induced super hydrophobicity	hydrophobe		
	self-cleaning	self-purifying (adj. verb) cathartic (adj.) sweeping (noun. and verb)		
	low adhesion	coherence (noun) constancy (noun) stickiness (noun)		
BEK…	……	……	……	……

Bionic Engineering Knowledge (BEK)

Mak and Shu [54] provided taxonomy of verbs that relate biological and engineering designs. Linsey et al. [55] indicated that functional annotations on diagrams raise the probabilities of effective biological analogies. Vincent et al. [56] presented ‘how’ of biologically inspired designs in its place of ‘what.’ Taking input from these researches, this work proposes indexing of bionic database with the help of a set of keywords. The keywords are accumulated based on the research and analysis of natural principles observed in biological systems along with morphological characteristics. Further, such descriptions are broken into noun or verb in the form entities, events or relations as shown in Table 2.

In this system, the user entered the design problem in the text. From existing set of keywords, the system detects some keywords list *[1…k]* for the design problem. Now user selects the appropriate database to search the keywords. After that, a binary search begins where the *lowerBound=1* and *upperBound=LENGTH(database)*. When the algorithm finds a match of required keyword in the index table (e.g., Table 1), it stored its descriptor (natural objects) in the *natural_objects_descriptor* field. Now algorithm gives output as a list of natural_objects_descriptor. The bionic information retrieval algorithm is shown below:

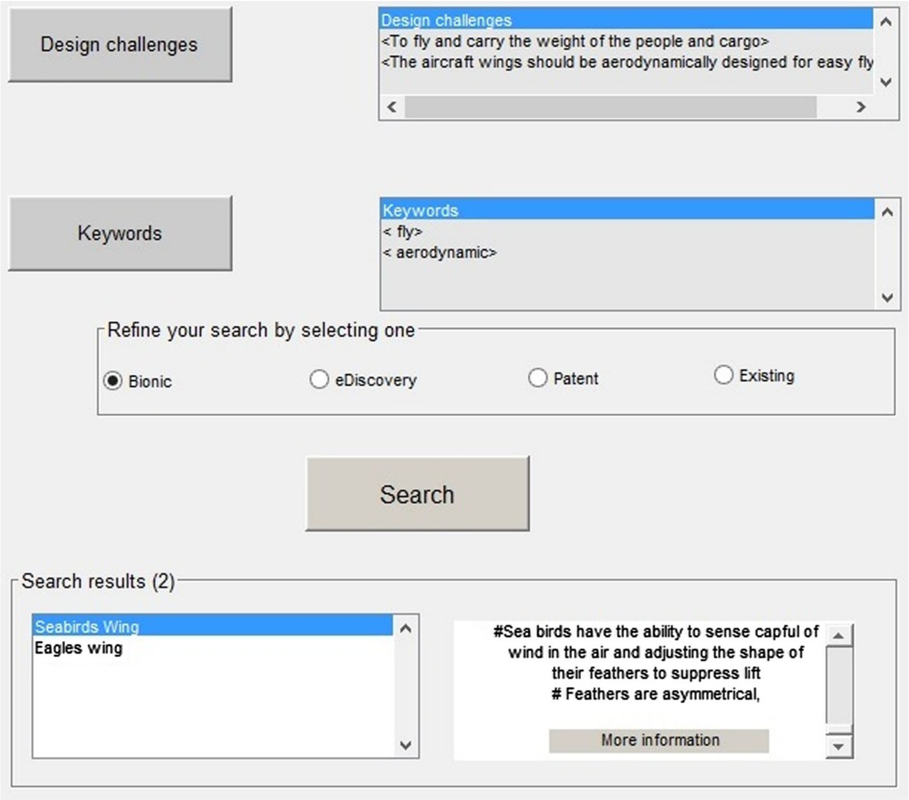
Algorithm - Searching Algorithm

```
BEGIN
INPUT REQUIREMENTS - (1) KEYWORDS (which are detected from the text entered by the user in 'Design Challenges' input box); (2) Selected Database
        [(a) Boinic, (b) eDiscovery, (c) Patent, (d) Existing].
    1.  Based on the keywords the algorithm will perform a binary search [52], (one keyword at a time).
    2.  list[1...k] is a list that contains total number of unique keywords that are detected; and natural_objects [1..k] will contain
        natural objects that will be searched by our algorithm for a specific keyword.
    3.  for i=1 to k; INCREMENT BY 1
          current_keyword = list[i];
          search current_keyword is selected database;
          USE BINARY SEARCH ALGORITHM;
                START BINARY SEARCH
                SET low=1 and high=LENGTH(database);
                while(low<=high)
                    mid=(low + high)/2;
                    if(database[mid]==current_keyword)
                        natural_objects[i]=database[mid];
                        natural_objects_descriptor[i] = database[mid].descriptor;
                        break;
                    else if(database[mid] > current_keyword)
                        high = mid - 1;
                    else if(database[mid] < current_keyword)
                        low = mid + 1;
                end while
            END BINARY SEARCH
        end for
    4.  For each keyword, contents of the natural_objects_descriptor array are the final results.
END
```

For the example of aircraft design, design challenges are fed as input, and accordingly, the system generates some keywords and searches the related bionic artifact (Fig. 3). We have seen that the keyword for the first problem is “fly” and “aerodynamics,” for second is “self-cleaning,” and for the third problem is “emission.” On the basis of these keywords, the bionic artifact in the bionic archive is searched. The bionic archive contains the knowledge with index as shown in Table 1. In bionic archive, the keywords of the problems are matched with the available knowledge index. Here, for the first design challenge, two bionic artifacts are detected: one is ‘sea birds wings’ and the other is ‘eagle’s wings.’ For the second, bionic artifact ‘lotus leaf’ is detected, and for the third challenge, ‘butterfly wings’ is detected. Basic local alignment search tool (BLAST) is a common tool for conducting similarity searches among the object. After detecting the biological artifact, the detailed solution is a matter of scientific study that involves examining what can be extracted, learned and duplicated from the natural world.

On the basis of available information (from Fig. 3 and Table 1), the following biological inspirations or knowledge to develop new engineering solutions for aircraft design can be deduced:

- Sea birds have the ability to sense gust/capful of wind in the air with their beaks and react by adjusting the shape of their feathers to suppress lift. On the basis of this knowledge, it is good to design moveable wing surfaces for more efficient flight. This would also help reduce the fuel consumption.
- The eagle’s wings perfectly balance maximum lift with minimum length by curling feathers. This adjustable feathers support the eagles from capful of wind. If the aircraft wing can mimic the upward curl of the eagle’s wings, enough lift would be generated for efficient flying. Due to the adjusting property of wings (as per wind direction), less effort is made by the engine for flying; thus, fuel is saved, due to its capability to curl wings, lees space is required, and in such a case, lesser space would be required for parking.



Design challenges
<To fly and carry the weight of the people and cargo>
<The aircraft wings should be aerodynamically designed for easy fly

Keywords
< fly>
< aerodynamic>

Refine your search by selecting one
● Bionic ○ eDiscovery ○ Patent ○ Existing

Search results (2)
Seabirds Wing
Eagles wing

#Sea birds have the ability to sense capful of wind in the air and adjusting the shape of their feathers to suppress lift
Feathers are asymmetrical,

Fig. 3 Information retrieval system

- The surface of a lotus leaf has self-cleaning properties. Dirt particles are picked up by water droplets due to the micro- and nanoscopic architecture of the surface, which minimizes the droplet's adhesion to the surface. This property inspires to develop coatings for cabin fittings, which shed water in the beads and take dirt or contaminants with them. The process would improve hygiene.
- Fluorescent patches on the wings of African swallowtail butterflies work in similar manner to high-emission light emitting diodes (LEDs). Same technique can be used for aeroplanes. This ontology helps to recognize the aircraft's position in low-visibility conditions both visually to ground staff/pilots and satellite imaging.

On the basis of above bionic-based reasoning (BBR), the designer may develop a model for analysis and simulations. In this example of aircraft design, a knowledge map based on bionic knowledge reuse process is presented, which helps to build a framework of knowledge map system.

While designers have used nature as an inspiration, no standard process exists specific to the practice of nature-inspired design. Biomimicry [57], spiral design [58] and bio-inspired design [59] are three most popular existing methods to support the generation of bionic designs. However, a few gaps are still unplugged to lead to establishment of a successful bionic design method.

- The biomimicry design method is unable to satisfy multiple requirements with design optimization. In biomimicry, iteration is missing to pursue optimization.
- The spiral design method does not explicitly consider a way to guide the quest to satisfy multiple requirements.
- The bio-inspired design method also shows gaps in design optimization. This method is more focused on the set of function requirement, rather than proposing the optimal form.

From the above, two common gaps are identified. One is of multiple requirements, and another is design optimization. Only one of the three methods (the spiral design method) entails some evaluation procedures, albeit limited in scope. To fill this gap, this work proposes a normative process to reuse design methodologies prevalent in nature or inspired by biology. The solution for most of the design problems can be developed by taking inspiration from the biological systems, with the help of proposed seven-step design process as enumerated below. The seven steps are:

(i) Problem identification
(ii) Keyword(s) determination (of the problem) and its search in bionic archive
(iii) Biological system selection
(iv) Analogy of the artifact with the problem
(v) Knowledge abstraction
(vi) Product development based on abstracted knowledge
(vii) Solution evaluation

The tasks carried out during each of these seven steps are outlined below:

1. Problem Identification

Identifying customers' fresh needs or unmet needs, specific design problems and their proper understanding is the first critical step to successfully implement the methodology. Once the problem is properly defined, it is relatively easy to generate keywords.

2. Keyword determination (of the problem) and its search in bionic archive

A keyword, typically one or two words, is used to describe the problems in design and searched when bionic archive is explored. For example, in a jogging shoe, the customer expects that while running, the shoe provides even feeling and not the jarring transition that may result in shoe pinching due to stiffness. Hence, after problem refinement and analysis, the objective functions or keywords while designing a jogging shoe are lightweight, zero drop, and ultra-flexibility. After determining the keywords, the bionic archive is explored for the solution. If the solution is not available in bionic archive, the same problem is searched in nature and natural way is adopted to solve the problem.

3. Biological system selection

A biological system is selected after detecting the bionic index with respect to the keywords. It may be possible that the program detects two or more biological systems. In this situation, designer compares solutions available in the biological artifacts and finds an organism or a system that survives in the most similar case, as the problem being explored.

4. Analogy of the natural system with the product

After search and selection, the designer identified the structures and superficial mechanisms from the biological system that are related to the problem. Through the BBR, information of functional analysis, morphology and structure of biological system, the designer sets some mathematical, geometrical and statistical principles between the biological system studied and the product to design.

5. Knowledge abstraction

The knowledge is abstracted from the adherent analogy, most relevant to a particular design challenge. For instance, design of jogging shoe involves study of bear and its legs. The bears are generally bulky and robust animals with relatively short legs. Their legs have highly differentiated bone structures. Foot top is fully covered with hair. However, for complex products/geometry, functional decomposition during the problem definition step helps in facilitating the understanding of the biological solutions. After studying the recorded facts for shoe design, following parameters are recommended:

- Shoe with a curve at the bottom.
- Generous toe box and vamp area along with an articulated sole allows the toes and foot greater freedom of motion.
- A series of distinct anatomical cushions within the foot helps to protect bone and muscles from the impact.

6. Product development based on abstracted knowledge

Translation of the bio-inspired solutions involves interpretation of one domain space (e.g., biology) into another (e.g., mechanics) by introducing new constraints. After a solution is well understood, important principles are extracted into a solution-neutral form, which required descriptions that removed as many specific structural and environmental constraints as possible. Here, the designer translates the principle from biological to mechanical domain by introducing new constraints. In the case of designing a shoe for poor road conditions, new criteria of weight, flexibility, impact resistance and manufacturing process are added, along with refined affordances, for example, in materials.

7. Solution evaluation

This step identifies ways to improve the design and bring forward questions to explore issues such as those related to design modification or design variety, shape and size, additions or refinements, etc. This process is done through a procedure named bionic reverse engineering, the details of which are provided in Sect. 4.2.

3.2 Design reuse and uncertainty minimization

Duffy and Ferns [21] concluded that even though the concept of design reuse is accepted as a valid approach to design, little endeavor has been made to formalize the components that outline reuse. They then proposed design reuse models based on the interaction among six knowledge resources, namely domain knowledge, domain model, reuse library, evolved design model, complete design model and design requirements. Designers can have difficulties in identifying relevant designs for reuse, especially as the search for information proceeds back in time and the amount of information available increases. Nature being the best school for designer, this work integrates bionic archive with Duffy and Ferns [21]; Duffy et al. [2] design reuse model. On the basis of bionic application, an improvised model is proposed as shown in Fig. 4.

Designer selects some requirement for a specific problem statement to be incorporated in design. After that, design reuse involves various activities that utilize existing technologies to address new design requirements. In order to apply design reuse, it is required that a set of designed products must exist and the related design information is accessible. Here, a bionic archive is available where a collection of designed products exists. In general, the design of products involves a complicated process of mapping from the functional domain to

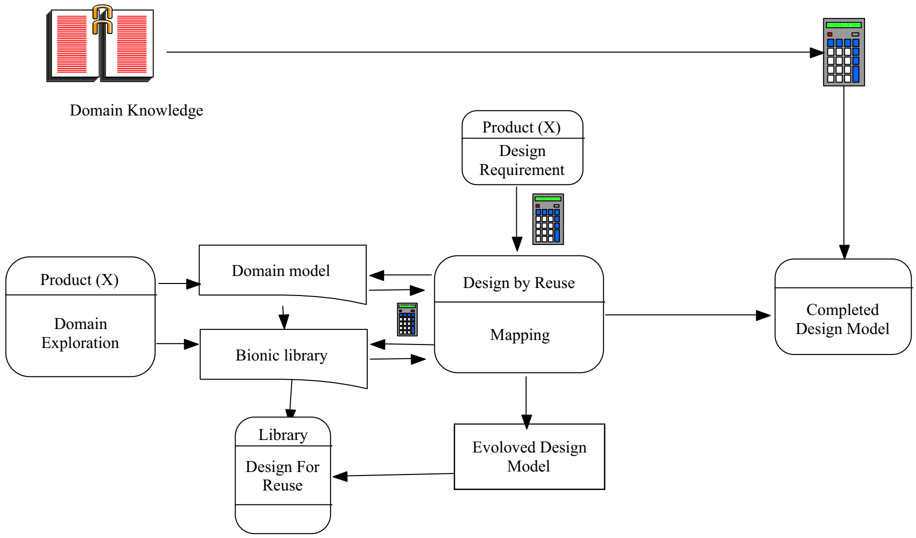


Fig. 4 Bionic design reuse model

the physical domain. Hence, a domain model that represents the designer conceptualization of design has been presented here. This domain model is connected with the bionic library. Domain exploration understands the design picture and identifies extracts and stores reusable design. Evolved design looks at any level of abstraction that can be reused and the complete design models take care of comprehensive definition of new design.

4 Case study

This section presents the implementation of the proposed methodologies illustrate the design of a shoe meant to maneuver poor road conditions. The proposed case study is divided into two sections. The first part presents brief implementation of the seven-step design reuse methodology by analyzing the design problem and developing a solution for the problem of designing the shoe for the given conditions. Section 4.2 presents mitigation of information uncertainty in product design by reusing previous design knowledge to improvise the design process.

4.1 Implementations of bionic design reuse

This part presents a brief implementation of the seven-step design methodology by analyzing the design problem and developing solution for the problem of designing a shoe meant to maneuver poor road conditions. The methodology is applied as follows:

I. Problem: Design a shoe that is useful for walking as well as running when the road conditions are not conducive.
II. Keywords: Low weight, sufficiently flexible, impact resistant
III. Keywords search in bionic archive: The natural solution relevant to the problem identified is the design inspired by bears' paws

Table 3 Analogy of the artifact with the problem on the basis of literature

S. no.	Bear	Human
1.	Average dimensions of front feet are 11.43 cm in length and 10.16 cm in width. Rear feet are 17.78 × 8.89 cm.	North American adult Caucasian males (mean age 35.5 years) have an average foot length of 26.3 cm with standard deviation of 1.2 cm
2.	Each toe has a thick, curved, non-retractile claw	The heel bone and ankle makes the hind foot
3.	Claws of the bear are very sharp	Not very sharp
4.	To help protect their feet, there are pads at the bottom	Bottom are slightly soft, i.e., no pads
5.	Pads are designed to give them plenty of traction for walking on the slippery ice	No any pads, incapable to walk on slippery surfaces
6.	Paw skeleton is very similar to that of a human or a child's foot	The human foot and ankle is a strong and complex mechanical structure containing 26 bones, 33 joints
7.	Rear foot has the heel while the front does not	No heel
8.	…	…

IV. Analogy of the artifact with the problem: As per the available literature [60], bear paws and human hands and feet have good correlation in terms of overall size and shape; however, both have different advantages and limitations. Analogy between the bear's paw and human feet is shown in Table 3.

V. Knowledge abstraction

(a) Bears are generally bulky and robust animals with relatively short legs.
(b) Legs have highly differentiated bone structures.
(c) Foot top fully covered with hair. Bottom is flexible so that the bear is able to walk on mud as well as on improper roads.
(d) Rear foots have the heel.
(e) Stocky wide legs help distribute the weight. Paws are covered with soft leather.
(f) Running speed of a bear is approximately 48 km per hour.
(g) Paws covered with soft leather and long hair help to maintain the temperature.

VI. Product development based on abstracted knowledge: The designer is supposed to translate the biological principles into mechanical domain by introducing new constraints. Bear foot length, girth, basic width, heel height are translated to the corresponding data for human foot. Proposed design extracts key parameters from bionic data and reuses/ resets parameters for designing the shoe. Here, the goal is to parameterize the given bionic data set and produce a product from the bionic data by changing the extracted key parameters. Editing this bionic set of parameters would result in different shoe-last product models. This is important for effective integration of bionic engineering with the development and manufacturing process. Table 4 shows the parameters that may be used to translate biological data into mechanical domain. Once the parameters are identified, effective constraints/mapping rules have to be evolved. The mapping of biological knowledge to mechanical data is shown in Fig. 5.

VII. Solution evaluation: Based on the expected solution and evaluation of the prototypes built, the parameters that do not meet the constraints are modified. This evaluation

Table 4 Product definition parameters for shoe last that are define by ISO standard

S. no.	Product definition parameters
1.	Girth
2.	Heel height
3.	Length
4.	Toe height
5.	First metatarsal height
6.	Ball girth
7.	Instep girth
8.	Height of medial malleolus
9.	Fifth toe angle
10.	………………

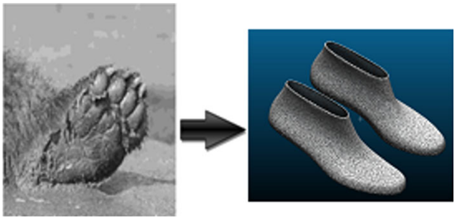


Fig. 5 Translation from biological to mechanical domain

and modification process is done by bionic reverse engineering and demonstrated in Sect. 4.2.

4.2 Uncertainty mitigations

The design of a new product normally starts with a limited knowledge, and therefore, the designers suffer due to lack of sufficient design knowledge, which may lead design uncertainty. This challenge is reduced if suitable bionic design knowledge and concepts, which are freely available in nature, can be reused (see Fig. 2). During product design, determination of parametric value of design is a challenging task. As shown in Figs. 6 and 8, this work also helps in determining optimum parametric values of the concerned product. Kumar and Tandon [61] had highlighted that product development process includes factors like technical parameters, material properties, functional and geometrical interdependence. This work exhibits prior information of all these involves factors along with significance of a bionic and design reuse methodology to facilitate the smooth process of product development.

The precise information required to address the design problem may be accessed with the help of bionics. Bionic information can be deduced either through imitating the model or functional behavior (biomimicry) or by analyzing the behavior (nature inspired). In this work, an attempt has been made to emulate biomimicry through a process, which extracts knowledge or design information from bionic artifacts. We have labeled this process as bionic reverse engineering (BRE). The concept of BBR is very similar to case-based reasoning (CBR). The revised manuscript discusses the BBR process, which includes the following steps: involved

(i) Retrieve bionic knowledge
(ii) Reuse the accumulated design knowledge relevant to the design problem in hand
(iii) Revise, if necessary, the bionic knowledge with respect to the existing problem
(iv) Retain this knowledge in bionic library to create design knowledge archive

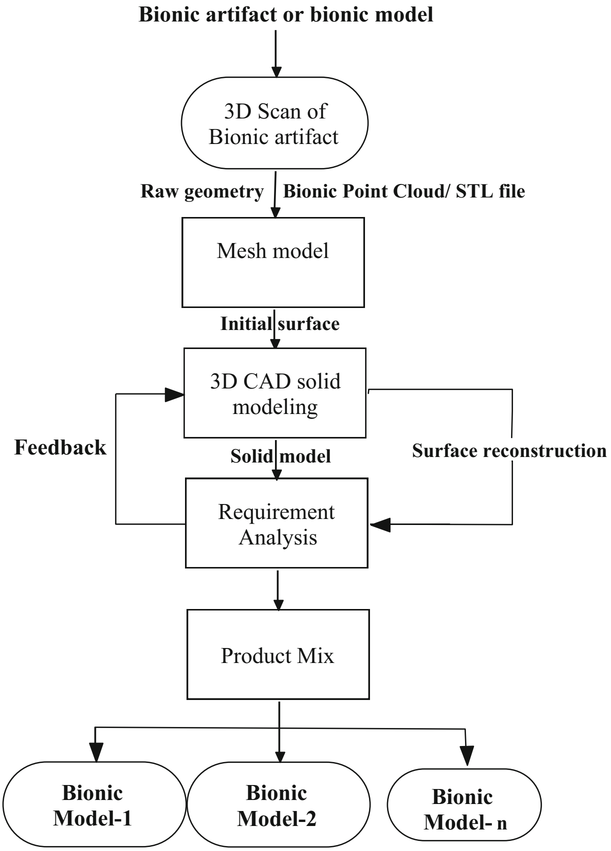


Fig. 6 Work flow of bionic reverse engineering

Here, with the help of bionic artifacts, key product parameters are extracted from the scanned data, which is then reused for mass customization and designing a new product as shown in Fig. 6.

Figure 6 also depicts the work flow of bionic reverse engineering process. Here, knowledge or design information is first extracted from bionic artifacts, and then, the product is reproduced based on the extracted information. The most important step is to first select the appropriate bionic artifact and then proceed for digitization. The initial geometry after BRE is obtained in the form of point cloud, which may be converted to a polygon mesh for three-dimensional (3D) applications. This mesh model is a low-level digital shape and can be used to adjust freeform surfaces. This low-level digital shape needs to be imported into a 3D computer aided design (CAD) environment. With the help of CAD software, a set of bionic artifact points that lie close to the desired, yet may be unknown surface, is identified. This set of bionic artifact points is then manipulated to construct a surface model that approximates the desired surface. As per the design requirement, this surface patch is analyzed for desirable modifications or mass customization. This is an iterative process. The result of this iteration is an optimized digital model of the new product form. One such product form may be used to create product families by varying the perceptive parameters and editing the constraints (i.e., extracted features like radius, angles, curvature).

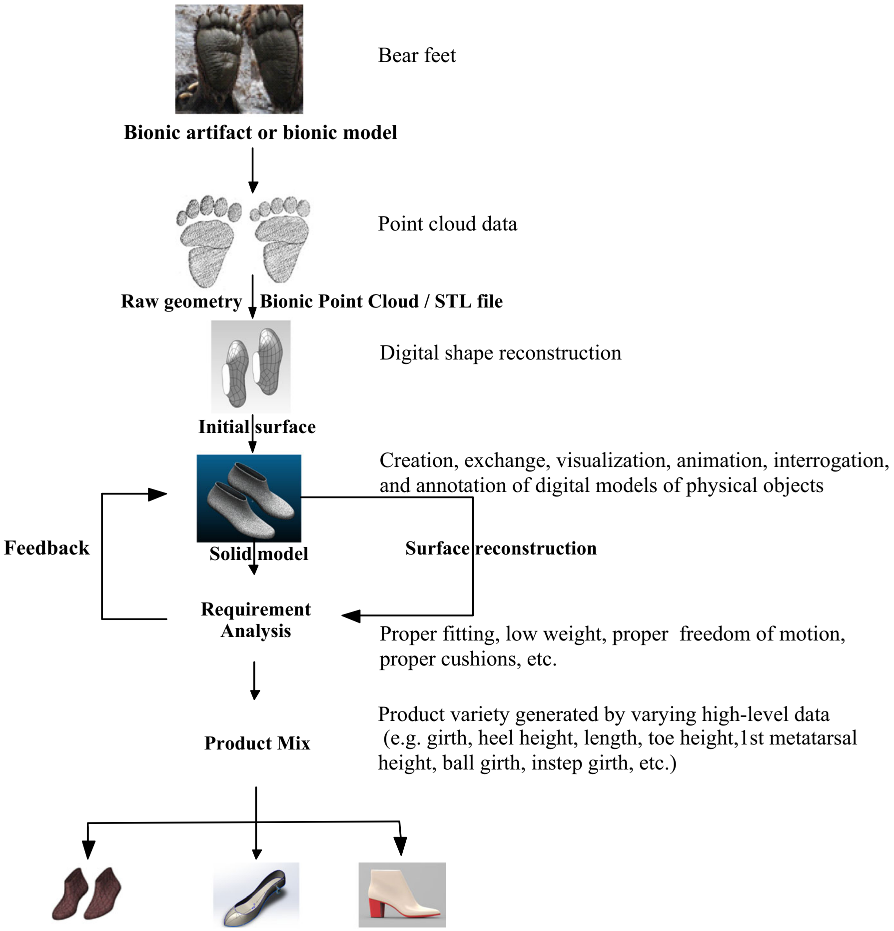


Fig. 7 An illustration of Bionic RE modeling of a bear leg by CAD based modeling strategy

Figure 7 presents an illustration of BRE for designing human shoes with bear paw as bionic artifact by using the proposed modeling strategy. The example illustrates solving one of the design problems to help generate bionic design concepts. With the help of 3D scanners, a point cloud was created and later a mesh was generated by preprocessing the point cloud data. This mesh model gave rough idea of parameters for shoe design that were earlier uncertain. The mesh model of bionic bear feet provided information about some of the freeform surface parameters that may be used for human shoe design, and accordingly some features of shoe were extracted. Thus, some unknown parameters were known before hand and later by manipulating the geometric data and knowledge, conceptual data models were developed, as shown in Fig. 7. For this purpose, the uncertain design parameter (y) is defined in terms of bionic certain quantities ($C_1, C_2 \cdots C_n$), with the help of functional relation f, as given below:

Here, c_i is the parametric value of a bionic feature and function f is a correlation factor that would help provide definite value to measurement uncertainty. For example, in this case,

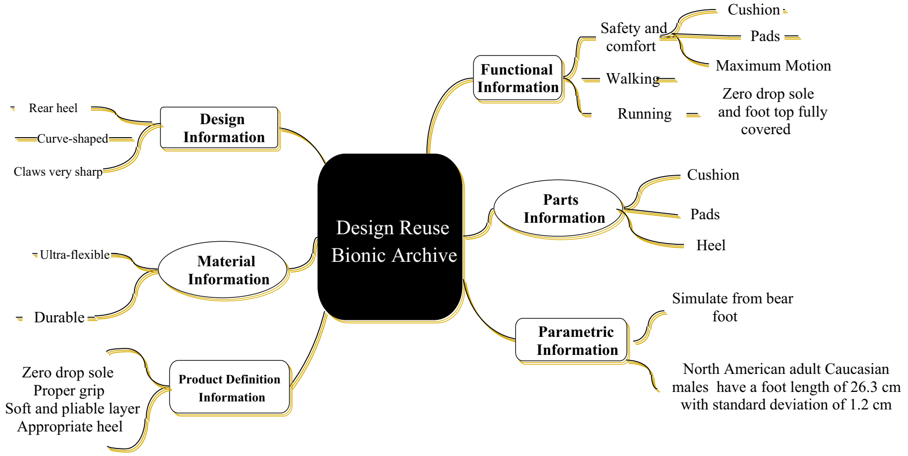


Fig. 8 Various uncertainty minimizations through bionic design reuse

the known information is the length of bear rear foot [$C_j = 11.78\,\text{cm}$ (average)]. On the basis of this information, we can evolve the value of uncertain parameter, here, average length of human foot as;

$$= (\text{Correlation factor}) \times (\text{parametric value of bear rear foot})$$

For 50th percentile of human foot length (y_j), the value of correlation factor would be 2.2325 s.t. average length of human foot comes out to be

$$y = 2.2325 \times (11.78) = 26.3\,\text{cm}$$

For unknown quantities, design of experiments has to be performed to find the exact value of correlation factor 'f.' However, functional relation f is subjected to experience and knowledge of designer, as well as behavior and property of the relevant parameter. This technique would help represent and manipulate bionic parameters (e.g., girth, heel height, length, toe height, 1st metatarsal height, ball girth, instep girth, height of medial) to the proposed product parameters.

Next stage of bionic reverse engineering is to check whether the product is able to fulfill the desired needs or not. The designer needs to check the proposed model's ability to satisfy architectural, structural, behavioral, functional (both core and ancillary functional), non-functional, performance, design, derived, and allocated requirements. If the designed product is not able to satisfy the requirements, the designer may have to modify the design with the help of CAD package.

As the human fee is of various sizes and even varying shapes, it would be advisable to develop a product mix that would help the company to satisfy different customers' requirements by offering a wide range of shoe styles and sizes, which can be done by varying the product design parameters.

Design of any product requires a number of information regarding functional parameters, design parameters, technical parameters, material properties, geometrical parameters, etc. It is too complicated to provide the precise information. Through BBR, design reuse can minimize information uncertainties reasonably as shown in Fig. 8. As in case presented, the parameters that are uncertain for shoe design, like girth, heel height, length, toe height, 1st metatarsal height, ball girth, instep girth, height of medial malleolus, 5th toe angle, can be

Table 5 Various design parameters identify through bionic design reuse

S. no.	Uncertain parameter	Certain parameter or knowledge
1.	Parameter	Bear foot parameter
2.	Product definition parameters	Lightweight, zero drop, and ultra-flexible running shoe
3.	Cushioning	The sole is mostly devoid of rubber, where midsole and sole are one and the same piece of material
4.	Sole and grip	Zero drop sole and foot top fully covered for proper grip
5.	Support	Soft and pliable layer wraps muscles, bones and tendons to protect and support the entire foot
6.	Contact area	When standing barefoot, the heel contacts the ground neutral to the forefoot
7.	Safety	A series of distinct anatomical cushions within the foot help protect bone and muscles from the energy of impact

easily obtained through bionic bear feet as shown in Table 5. Hence, with bionic reuse library, the information uncertainties are minimized.

5 Summary and conclusion

In design, availability of knowledge and information sources is critical for decision makers to make the best possible design decision at the right time. During initial stages of product development, generally appropriate and complete knowledge and information is not available to designers. This work discusses the application of bionics to support design reuse. A bionic-based design reuse model has been proposed for efficient collection of knowledge and information to minimize information uncertainty. On the basis of this research, guidelines for design reuse are:

Step-I Identification of suitable keywords with respect to the design problem
Step-II Identification of relevant bionic artifact with respect to the given keywords and accordingly retrieval of bionic design information (refer Figs. 2 and 3)
Step-III Supplying of this bionic design information in the knowledge resources; design reuse model (refer Fig. 4) for new product design.
Step-IV Optimization of new product design parameters with the application of bionic reverse engineering (refer Figs. 7 and 8)

With bionic design reuse, design information (i.e., product definition parameters) is accrued and with the proposed bionic design process, designers are benefitted from the previous domain knowledge. Bionic solutions provide easy indexing and retrieval for reuse of relevant designs. Through the example, it is clear that bionic-inspired design hold significant potential, although it is yet to be fully realized. Design reuse has a problem of design fixation. It is minimized through coupling of bionic design and existing design reuse archive. With the help of some examples, we presented the knowledge map based on bionic knowledge reuse process and its support to product design and thus build a framework of knowledge map system. However, further research is required to make a bionic archive of design inspirations and information. The major contribution of this work includes

- As designers have indexing and retrieval problem, a bionic indexing system is proposed to solve this. Bionic solutions provide easy indexing and retrieval for design reuse.

- As bionic design is still not a standard process, for bionic design process, a seven-step process has been proposed in this work. For design reuse in engineering practice, formal bionic guidelines allow designers to effectively benefit from previous domain knowledge.
- The present bionic design method shows gaps in design optimization. To cope up with this, bionic reverse engineering can be employed to optimize digital model of a new product form.

References

1. Regli WC, Cicirello VA (2000) Managing digital libraries for computer-aided design. Comput Aided Des 32(2):119–132
2. Duffy AHB, Smith JS, Duffy SM (1998) Design reuse research: a computational perspective. In: Sivaloganathan S, Shahin TMM (eds) Proceedings of engineering design conference '98 on design reuse, professional engineering publishing limited, London, June 1998, pp 43–56
3. Duffy SM, Duffy AHB, MacCallum KJ (1995) A design reuse model. In: Proceedings of the international conference on engineering design (ICED 95). Heurista, pp 490–495. ISBN 3856930280
4. Court AW, Culley SJ, McMahon CA (1993) The information requirements of engineering designers. In: Proceedings of the international conference on engineering design
5. Baudin C, Gevins J, Baya V, Mabogunje A (1991) Dedal: using domain concepts to index engineering design information. In: Proceedings of the ninth national conference on artificial intelligence, AAAI, Anaheim, CA, pp 702–707
6. Yang M, Cutkosky M (1999) Machine generation of thesauri: adapting to evolving vocabularies in design documentation. In: Proceedings of the international conference on engineering design ICED99
7. Zhang WY, Tor SB, Britton GA (2006) Indexing and retrieval in case-based process planning for multi-stage non-axisymmetric deep drawing. Int J Adv Manuf Technol 28(1–2):12–22
8. Ormerod TC, Mariani JA, Ball LJ, Lambell NJ (1999) Desperado: three in-one indexing for innovative design. In: Sasse MA, Johnson C (eds) Proceedings of the seventh IFIP conference on human–computer interaction—INTERACT '99. IOS Press, London, pp 336–343
9. Ball LJB, Lambell N, Ormerod TC, Slavin S, Mariani J (1999) Representing design rationale to support innovative design reuse: a minimalist approach. In: Proceedings of 4th design thinking research symposium on design representation, March 1999. MIT, Cambridge, MA
10. Peng C, Cerulli C, Lawson B, Cooper G, Rezqui Y, Jackson M (2000) Recording and managing design decision-making processes through an object-oriented framework. In: 5th international conference on design and decision support systems in architecture and urban planning
11. Altmeyer J, Ohnsorge S, Schürmann B (1994) Reuse of design objects in CAD frameworks. In: Proceedings of the 1994 IEEE/ACM international conference on computer-aided design. IEEE Computer Society Press, pp 754–761
12. Altmeyer J, Schürmann B (1996) On design formalization and retrieval of reuse candidates. In: Artificial intelligence in design'96. Springer Netherlands, pp 231–250
13. Preece A, Hui KY, Gray A, Marti P, Bench-Capon T, Jones D, Cui Z (2000) The KRAFT architecture for knowledge fusion and transformation. Knowl Based Syst 13(2):113–120
14. Preece A, Hui K, Gray A, Marti P, Bench-Capon T, Cui Z, Jones D (2001) KRAFT: an agent architecture for knowledge fusion. Int J Coop Inf Syst 10(01n02):171–195
15. I-Iuhns MN, Acosta RD (1992) Argo: an analogical reasoning system for solving design problems. Artif Intell Eng Des Vol II Models Innov Des Reason Phys Syst Reason Geom 2:105
16. Aamodt A, Plaza E (1994) Case-based reasoning: foundational issues, methodological variations, and system approaches. AI Commun 7(1):39–59
17. Maher ML, de Silva Garza AG (1996) Developing case-based reasoning for structural design. IEEE Intell Syst 11(3):42–52
18. Maher ML (1997) Casecad and cadsyn. Issues and applications of case-based reasoning in design, pp 161–185
19. Pearce M, Goel AK, Kolodner JL, Zimring C, Sentosa L, Billington R (1992) Case-based design support: a case study in architectural design. IEEE Expert 7(5):14–20
20. Lee CK, Lau HC, Yu KM, Fung RY (2004) Development of a dynamic data interchange scheme to support product design in agile manufacturing. Int J Prod Econ 87(3):295–308
21. Duffy AHB, Ferns AF (1999) An analysis of design reuses benefits. In: Proceedings of the 12th international conference on engineering design (ICED '99). Design Society, pp 799–804

22. Duffy AH, Persidis A, MacCallum KJ (1996) NODES: a numerical and object based modelling system for conceptual engineering design. Knowl Based Syst 9(3):183–206
23. Gu P, Hashemian M, Nee AYC (2004) Adaptable design. CIRP Ann Manuf Technol 53(2):539–557
24. Zhang Y (1998) Computer based knowledge modeling and management to support design evolution. Ph.D. thesis, CAD Centre, University of Strathclyde, 75 Montrose Street, Glasgow G1IXJ, United Kingdom
25. Gozali F (2013) Case based reasoning in engineering design. Jurnal Teknik Elektro 2(1):13–28
26. Ascough Ii JC, Maier HR, Ravalico JK, Strudley MW (2008) Future research challenges for incorporation of uncertainty in environmental and ecological decision-making. Ecol Model 219(3):383–399
27. Walker WE, Harremoës P, Rotmans J, van der Sluijs JP, van Asselt MB, Janssen P, Krayer von Krauss MP (2003) Defining uncertainty: a conceptual basis for uncertainty management in model-based decision support. Integr Assess 4(1):5–17
28. Sigel K, Klauer B, Pahl-Wostl C (2010) Conceptualising uncertainty in environmental decision-making: the example of the EU water framework directive. Ecol Econ 69(3):502–510
29. Chowdhury S, Gibb F, Landoni M (2011) Uncertainty in information seeking and retrieval: a study in an academic environment. Inf Process Manag 47(2):157–175
30. Otegi A, Arregi X, Ansa O, Agirre E (2015) Using knowledge-based relatedness for information retrieval. Knowl Inf Syst 44(3):689–718
31. Huang Y, Jiang Z, Liu L, Song B, Han L (2015) Building a knowledge map model situated in product design. Int J Inf Technol Manag 14(1):76–94
32. Xu Y, Hu LC, Zeng W, Jin B (2010) Web-service-based parametric design reuse for parts. Int J Adv Manuf Technol 46(5–8):423–429
33. Jin B, Teng HF, Wang YS, Qu FZ (2008) Product design reuse with parts libraries and an engineering semantic web for small-and medium-sized manufacturing enterprises. Int J Adv Manuf Technol 38(11–12):1075–1084
34. Vianello G, Ahmed-Kristensen S (2012) A comparative study of changes across the lifecycle of complex products in a variant and a customised industry. J Eng Des 23(2):99–117
35. Ong SK, Guo DO (2006) An online Web-based environment for detailed design reuse. Int J Adv Manuf Technol 27(5–6):462–467
36. Busby JS (1999) The problem with design reuse: an investigation into outcomes and antecedents. J Eng Des 10(3):277–296
37. Jin Xu, Shi Bairu, Zheng Lichen, Pei Xiaohan, Zhang Xiyao, Sun Ziqi, Yi Du et al (2014) Bio-inspired multifunctional metallic foams through the fusion of different biological solutions. Adv Funct Mater 24(18):2721–2726
38. Wen HI, Zhang SJ, Hapeshi K, Wang XF (2008) An innovative methodology of product design from nature. J Bionic Eng 5(1):75–84
39. Zheng Y, Gao X, Jiang L (2007) Directional adhesion of superhydrophobic butterfly wings. Soft Matter 3(2):178–182
40. Xia F, Jiang L (2008) Bio-inspired, smart, multiscale interfacial materials. Adv Mater 20(15):2842–2858
41. Liu K, Jiang L (2011) Bio-inspired design of multiscale structures for function integration. Nano Today 6(2):155–175
42. Koch K, Bhushan B, Jung YC, Barthlott W (2009) Fabrication of artificial Lotus leaves and significance of hierarchical structure for superhydrophobicity and low adhesion. Soft Matter 5(7):1386–1393
43. Bhushan B (2009) Biomimetics: lessons from nature—an overview. Philos Trans R Soc A Math Phys Eng Sci 367(1893):1445–1486
44. Stegmaier T, Linke M, Planck H (2009) Bionics in textiles: flexible and translucent thermal insulations for solar thermal applications. Philos Trans R Soc A Math Phys Eng Sci 367(1894):1749–1758
45. Fratzl P (2008) Bone fracture: when the cracks begin to show. Nat Mater 7(8):610–612
46. Liu M, Wang S, Wei Z, Song Y, Jiang L (2009) Bioinspired design of a superoleophobic and low adhesive water/solid interface. Adv Mater 21(6):665–669
47. Yoshioka S, Kinoshita S (2002) Effect of macroscopic structure in iridescent color of the peacock feathers. FORMA TOKYO 17(2):169–181
48. Becker N, Oroudjev E, Mutz S, Cleveland JP, Hansma PK, Hayashi CY, Hansma HG (2003) Molecular nanosprings in spider capture-silk threads. Nat Mater 2(4):278–283
49. Swanson BO, Blackledge TA, Hayashi CY (2007) Spider capture silk: performance implications of variation in an exceptional biomaterial. J Exp Zool Part A Ecol Genet Physiol 307(11):654–666
50. Kroes P (2002) Design methodology and the nature of technical artefacts. Des Stud 23(3):287–302
51. Zhou B, Pei J (2012) Aggregate keyword search on large relational databases. Knowl Inf Syst 30(2):283–318
52. Zhang L, Liu Z, Li L, Shen C, Li T (2017) PatSearch: an integrated framework for patentability retrieval. Knowl Inf Syst 1–24. https://doi.org/10.1007/s10115-017-1127-0

53. Bentley JL (1979) Multidimensional binary search trees in database applications. IEEE Trans Softw Eng 4:333–340
54. Mak TW, Shu LH (2004) Abstraction of biological analogies for design. CIRP Ann Manuf Technol 53(1):117–120
55. Linsey JS, Wood KL, Markman AB (2008) Modality and representation in analogy. Artif Intell Eng Des Anal Manuf 22(2):85–100
56. Vincent J, Bogatyreva O, Bogatyrev N, Bowyer A, Pahl A (2006) Biomimetics: its practice and theory. J R Soc Interface 3(9):471–482
57. Junior W, Guanabara A, Silva E, Platcheck E (2002) Proposta de uma Metodologia para o Desenvolvimento de Produtos Baseados no Estudo da Biónica. P&D-Pesquisa e Design, Brasília
58. Biomimicry Institute (2007) Biomimicry—a tool for innovation. http://biomimicry.org/what-is-biomimicry/
59. Helms M, Vattam SS, Goel A (2009) Biologically inspired design: process and products. Des Stud 30:606–622
60. Gilbert BM (1993) Mammalian osteology. Missouri Archaeological Society, Laramie
61. Kumar P, Tandon P (2017) Classification and mitigation of uncertainty as per the product design stages: framework and case study. J Braz Soc Mech Sci Eng 39(11):4785–4806

Prabhat Kumar is a Ph.D. candidate in Mechanical Engineering discipline of IIITDM Jabalpur, India. He had graduated from Jabalpur Engineering College Jabalpur, India, where he studied Industrial Production Engineering. He received masters in Industrial Engineering and Management from Shri G.S. Institute of Technology and Science Indore, India. His research interests include Design under Uncertainty, Intelligent and Creative Product Design, Product and Process Improvements.

Puneet Tandon is a joint Professor of Mechanical Engineering and Design Discipline at PDPM Indian Institute of Information Technology, Design and Manufacturing (IIITDM), Jabalpur, India. He graduated in Mechanical Engineering from NIT, Kurukshetra, India, and received his Master and Doctoral degrees in Mechanical Engineering from Indian Institute of Technology Kanpur, India. He has authored more than 200 papers in referred journals and international conferences. His primary research interests include Product Design, Geometric Modeling, Computational Support to Product Design, Knowledge-based Engineering, Hybrid Manufacturing. He is very actively involved in sponsored research. He is Principal Investigator to numerous projects sponsored by various national and international funding agencies. He is on editorial board of a few international journals and has been reviewer to several international journals. He also actively participates in various international academic organizations.