A KNOWLEDGE-BASED IDEATION APPROACH FOR BIO-INSPIRED DESIGN

Chen, Liuqing (1,2);
Cai, Zebin (1);
Jiang, Zhaojun (3);
Long, Qi (4);
Sun, Lingyun (1,2);
Childs, Peter (5);
Zuo, Haoyu (5)

1: Department of Computer Science and Technology, Zhejiang University, Hangzhou 310030, China;
2: Singapore Innovation and AI Joint Research Lab, Zhejiang University, Hangzhou 310030, China;
3: School of mechanical engineering, Tianjin University, Tianjin 300350, China;
4: Zhejiang University-University of Illinois at Urbana-Champaign Institute, Haining 314400, China;
5: Dyson School of Design Engineering, Imperial College London, London SW7 2AZ, UK

ABSTRACT

Bio-inspired design (BID) involves generating innovative ideas for engineering design by drawing inspiration from natural biological phenomena and systems, using a form of design-by-analogy. Despite its many successes, BID approaches encounter research challenges including unstructured data and existing models that hinder comprehension and processing, limited focus on finding biological knowledge compared to defined problems, and insufficient guidance of the ideation process with algorithms. This paper proposes a knowledge-based approach to address the challenges. The approach involves transforming unstructured data into structured knowledge, including information about natural sources, their benefits, and applications. The structured knowledge is then used to construct a semantic network, enabling designers to retrieve information for BID in two ways. Furthermore, a three-step ideation method is developed to encourage divergent thinking and explore additional potential solutions by drawing inspiration and utilizing knowledge. The knowledge-based BID approach is implemented as a tool and design cases are conducted to illustrate the process of applying this tool for BID.

Keywords: Bio-inspired design / biomimetics, Big data, Design methods, Semantic network, Data-driven-design

Contact:
Zuo, Haoyu
Imperial College London
United Kingdom
hz2019@ic.ac.uk

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1 INTRODUCTION

Design-by-analogy is a design methodology that draws inspiration from a source domain to a target domain through analogical reasoning (Jiang et al., 2021). Studies have demonstrated that Design-by-Analogy (DbA) can aid designers in mitigating design fixation (Linsey et al., 2010) and enhance design ideation outcomes when utilizing DbA-related tools (Fu et al., 2013; Zuo et al., 2022; Shi et al., 2017; Sarica et al., 2020). Bio-inspired design (BID) is a form of design-by-analogy wherein innovative ideas are generated from natural biological phenomena and systems for engineering design. This methodology attempts to leverage biological designs already existing in nature and is gaining popularity among designers aspiring for design innovations. In recent years, many efforts have been made to develop databases and methods for BID approaches. There is ample evidence that biologically inspired design has led to many novel, useful, robust and efficient designs. Despite its many successes, BID approaches still encounters research challenges. The first challenge is the unstructured data and existing models which impose difficulties for engineering designers to comprehend whole bio-design cases efficiently and further processing; a further challenge is that BID tools focus on retrieving biological models for a defined problem with limited emphasis on finding biological knowledge of interest; the ideation process with retrieval is also not guided sufficiently and augmented with algorithms.

To address the challenges highlighted, this paper proposes a novel knowledge-based BID approach. The approach involves transforming unstructured data into structured knowledge, including information about natural sources, their benefits, and applications. This structured knowledge is then used to construct a semantic network, which allows designers to retrieve information for BID in two ways. Additionally, a three-step ideation method is developed to explore more potential solutions and support divergent thinking, providing a feature for drawing inspiration and utilizing knowledge. The knowledge-based BID approach is implemented as a tool and design cases are conducted to demonstrate the process of applying this tool for BID.

2 RELATED WORK

Bio-inspiration is a creative approach based on observing biological systems. In the field of engineering design, the approach has evolved into an innovative design method, namely bio-inspired design, which uses analogies to biological systems to develop solutions for engineering problems. Benefiting from natural selection and biodiversity (Vincent, 2009, Müller et al., 2018), bio-inspired design provides considerable potential to produce innovative solutions (Fu et al., 2014, Chirazi et al., 2019). There are two main different approaches to bio-inspired design, solution-driven and problem-driven. The former starts with a particular biological system, which performs a potential function applied to technical solutions. The latter begins with a practical engineering problem, which could be the development of a new product or the improvement of an existing product.

Since bio-inspired design plays a vital role in problem-solving and concept design, it has received substantial attention from various industries (Wanieck et al., 2017). According to Wanieck et al. (2017), existing bio-inspiration-related tools can be classified into databases or methods. A database is a collection of biological organisms, biological characteristics, biological construction principles, biological functions or the like. A method describes a way of doing a task during the process of biomimetics. In the research reported here, the focus in review of prior material was mainly on open-sourced and scientific paper-recorded database tools.

AskNature is a publicly available database of biological information classified by function. This database organizes biological information according to the biomimicry taxonomy (Deldin and Schuknecht, 2014, Goel et al., 2015), which is a hierarchy of functions of biological systems. AskNature allows users to retrieve biological information by keywords (Hooker and Smith, 2016). Graeff notes that AskNature is the largest database for bio-inspired design providing over 1700 pieces of biological information. DANE (Design by Analogy to Nature Engine) (Goel et al., 2015) is a computational tool and database of biological Structure-Behavior-Function (SBF) models. This tool requires manual input of information entries, and the representations of biological systems depend on the modeling experience of designers. Idea-Inspire 4.0 (Siddharth and Chakrabarti, 2018) is another computational tool that supports analogical design with multimodal representation: function decomposition model, text, function model, image, video, and audio. The tool provides access to a number of biological systems using a searchable knowledge base. Ontology-Explorer (Kozaki and

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Mizoguchi, 2014) is a web tool for the identification of biological models and exploring biomimetics databases. It is based on linked data techniques and allows the users to find important keywords so that they can search for meaningful knowledge from various databases. Design Study library (Goel et al., 2022) is another web-based digital library that collects case studies during their 8-years of teaching into a digital library, thus supporting analogical learning. IBID extracts knowledge of the function, structure, and portions of the causal mechanisms of biological systems from their natural language descriptions. This knowledge is organised as a Structure-Behavior-Function (SBF) model. Finally, it uses the SBF annotations to retrieve biology articles relevant to design queries.

To systematically elucidate these databases, we further provide a structured analysis of all works in Table 1 from the following aspects:

1) structural knowledge: whether the biological knowledge is well structured or not (just plainly documented);

2) method: solution-driven method, problem-driven method or both.

The structural data is to review whether the analogical data is structurally represented or documentation represented. Structural representation can indicate biological systems in an abstract form. The abstracted form needs to follow a certain design principle, such as Structure-Behaviour-Function (SBF) or Structure-Function Knowledge (SFK) (Helfman Cohen et al., 2014, Gleich et al., 2010), to describe the characteristics of the biological models. The documentation representation is to record the biological systems in pure text. Compared with documentation representation, the structured approach can enhance the designer's ability to conceive technical solutions (Cohen and Reich, 2016).

The design approach is to review whether the tools are developed for the solution-based or problem-driven approach of the BID. A tool that is classified as for the solution-based approach tends to start with the biological knowledge of interest and then tries to match the extracted underlying principles to a problem. If a tool is classified as being for the problem-driven approach only, it attempts to start with the given practical problem and then facilitate a problem-solving process of transferring biological strategies to technology as a solution. Furthermore, both solution-driven and problem-driven approaches can exist within one tool.

Table 1. The choices of structural data and method of BID tools

	Structural data	Design approach
AskNature	No	Both
DANE	Yes	Problem-driven
IDEA-INSPIRE 4.0	Yes	Problem-driven
Ontology-explorer	Yes	Problem-driven
Design Study Library	No	Problem-driven
IBID	Yes	Problem-driven

DANE, IDEA-INSPIRE 4.0, Ontology-explorer, and IBID organized their bio-design cases in a structural form using the SBF or SAPPIRE models. While these models provide a useful decomposition of a system for browsing, they do not effectively bridge the natural source and target domains (Siddharth and Chakrabarti, 2018). This limitation still imposes difficulties for engineering designers to encode and comprehend whole bio-design cases efficiently. By further checking the tool, Ontology-explore applies the structural representation in the form of a semantic network which further support biological retrieval and ideation. Semantic network technologies can facilitate biomimetics-based innovations because it helps integrate knowledge from heterogeneous sources and can apply algorithms from different requirements and viewpoints. While all classified tools facilitate the tasks of the problem-driven approach, only AskNature can facilitate the solution-driven approach at the same time. The solution-driven approach is not fully developed and embedded into tools, even if they are of the same importance.

In summary, these databases all support the BID process and contribute in some manner. A promising database tool could be constructed under a new structural framework, therefore, to help enhance the designer's efficiency to conceive technical solutions. Besides, since both problem-driven and solution-based approaches contribute equally to developing solutions for design problems (Jacobs et al., 2014), a sophisticated BID approach should present a designer with both approaches to retrieve the structured scientific biological knowledge. A further retrieval method for ideation method could be developed after the retrieval.

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3 KNOWLEDGE-BASED BID APPROACH

We propose a knowledge-based BID approach from the conceptual design process in accordance with the design requirements and development direction. The approach supports the BID ideation for designers from three elements: structural data, two patterns of BID, and retrieval method for ideation. Details about the three elements are described in the following sub-sections.

3.1 Structural data

To overcome the problem of unstructured bionic data and existing model, our approach structures bionic data by summarizing bio-design cases into three types of keywords: 'source,' 'application,' and 'benefits' as the fundamental layer of the BID approach. These three types of keywords together describe the most critical information of the bio-design case in the form of structured data. For each page providing a possibility for a bio-design case, the definitions of the three keywords are as follows.

- 'source': the natural and biological sources stated on the page.
- 'benefits': the features and advantages of the 'source' stated on the page.
- 'application': the scenarios or fields of the source that could potentially be applied stated on the page.

By extracting these design knowledge, designers can be informed about how knowledge in the biological domain is transformed into engineering concepts. For example, 'Paint inspired by lotus leaves creates self-cleaning and stain-resistant surface.' In this bio-design case, the 'source' is 'lotus leaves,' the 'benefits' are 'self-cleaning' and 'stain-resistant,' and the 'application' is 'paint.' Because lotus leaves have self-cleaning and stain-resistant properties, a particular application, paint, is created. Thus, bio-design cases can be described as information transfer links with three nodes in each link: 'source' ->' benefit' -> 'application' (called S-B-A link). Based on the three keywords and S-B-A links, a bionic semantic network is constructed as a carrier for storing structured data. Every keyword forms a node, and the direction of the S-B-A link is also applied in the semantic network. In order to eliminate confusion due to capitalization variations, all nodes in the semantic network have been normalized to lowercase letters. The keywords associated with the 'source' and 'application' nodes have been standardized as nouns, while the keywords for the 'benefits' node have been standardized as either 'verb + noun' or 'adjective + noun' phrases. Furthermore, the synonymous keywords, such as "flexibility" and "flexible," are merged according to semantic similarity. From the perspective of cognitive psychology, the semantic network is highly suitable for applying knowledge-based design for creativity by using structured data (Chen et al., 2019, Han et al., 2021).Therefore, the proposed approach employs the semantic network for potential BID ideation process. Compared with traditional BID, structured data is more supportive for the information retrieval process as it facilitates information exchange so designers can take less time to find suitable inspiration.

For implementation, this work uses information extraction techniques in natural language processing to summarize bio-design cases into 'source', 'application' and 'benefits'. This way, thousands of bio-design cases can be processed quickly, replacing the slow processing by hand.

3.2 Knowledge retrieval for two patterns of BID

There are two main different BID patterns (Fayemi et al., 2017; Shu et al., 2011), solution-driven and problem-driven BID. The former starts with a particular biological system, which performs a potential function applied to technical solutions. The latter begins with a practical engineering problem, which could be developing a new product or improving an existing product. Then designers search biological information, extract and transfer design knowledge to technical solutions.

In our approach, a semantic network based on structured bionic data is utilized for knowledge-based BID ideation process. Since the link of the semantic network has two directions, when developing the retrieval strategy of the semantic network, the input and output can be reversed according to the direction of the link. If the input is 'source', the output is related to 'benefits' and engineering applications that could potentially be applied based on the input biological term. In contrast, when the input is 'application', the output is biological sources and related 'benefits' that could be utilized as technical solutions to solve a practical engineering problem. These two retrieval strategies correspond, in turn to two patterns of BID: solution-driven and problem-driven BID, which are of the same importance in design-related activities.

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3.3 Three-step retrieval method for BID ideation

We propose a three-step retrieval method for BID ideation process with divergent thinking. Divergent thinking promotes idea generation tools by fostering creativity and encouraging exploration of multiple potential solutions (Childs et al., 2022). Inspired by the principles of divergent thinking, the retrieval method is shown in Figure 1. This method consists of three steps that provide information with different divergent depths, i.e., the information diverges with the increasing volume in each step sequentially. The results of the three steps are, in order, direct, related, and potential. The direct retrieval results are retrieved from the input and validated as they are derived directly from an authentic bio-design case. The second step presents related results. The result is a divergent result which represents a potential solution between the source and new target based on shared sub-functions of the parts of products. The third step presents potential results based on semantic similarities between the source and target. The result is a more divergent result which represents a potential connection between the source and another new target based on these semantically similar sub-functions.

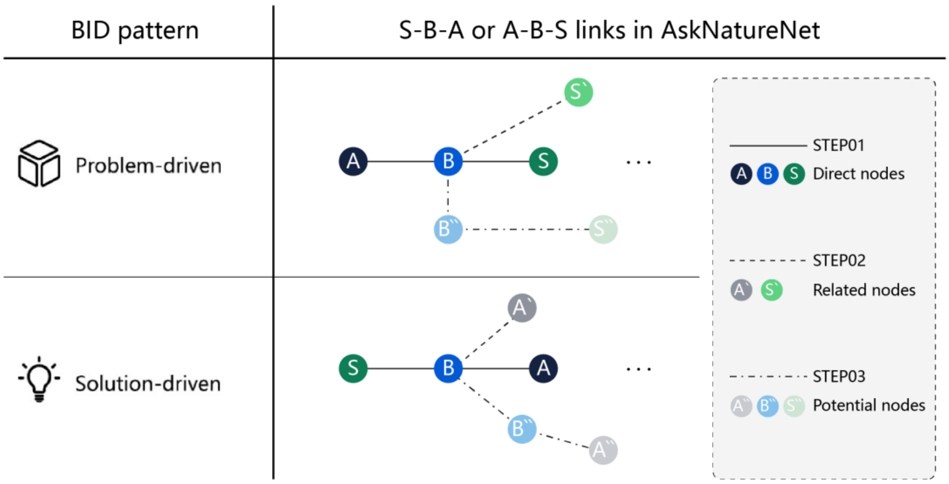

Figure 1. Three-step retrieval method for ideation

Taking the solution-driven pattern as an example. The definitions of these three steps are illustrated as follows. Assuming that the 'source' keyword entered in this case is Source_Origin.

- Step 01: In this step, the output is to find the S-B-A links where the Source_Origin is located. All the nodes are in the same S-B-A links as Source_Origin will be retrieved to show to designers. These 'benefits' and 'applications' mean direct benefits and direct applications. They give the designer the direction in which Source_Origin will most likely be applied.
- Step 02: The functionality of step two is to search reasonably extensional information based on direct benefits. All the S-B-A links which connect 'application' nodes and direct benefits nodes will be retrieved to show to designers. The output is related applications. This step shows more possibilities to employ the direct benefits obtained in step one to perform BID.
- Step 03: Step three provides extrapolated and divergent information. Notice that besides direct benefits, Source_Origin is likely to have other benefits (potential benefits), so similarity-between-benefits-oriented excavation can provide broader possibilities in the design process. These potential benefits can be obtained by calculating the semantic similarity with direct benefits in the semantic network. In order to determine the semantic similarities between the benefits nodes, the similarity metric S-BERT (Reimers and Gurevych, 2019) is utilized. S-BERT calculates the cosine similarity between the word embeddings of two nodes to determine the semantic similarity value. Then the potential applications linked to potential benefits would be retrieved. This step stimulates the divergent thinking of designers with a much more comprehensive range of ideas.

Compared to problem-driven BID, the difference with solution-driven BID is the replacement of the input with 'application' and reversing the data flow of the retrieval process.

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4 IMPLEMENTATION AND DESIGN CASE

4.1 Implementation

In order to demonstrate how the proposed knowledge-based BID approach would be applied, we constructed a tool to implement the approach named AskNatureNet. AskNatureNet stores a bionic semantic network based on structured data and develops an algorithm according to the proposed three-step retrieval method. It can be used to complete both solution-driven and problem-driven BID ideation. The interface of AskNatureNet is shown in Figure 2. The upper part of the interface is the input section, where designers input the keyword they would like to retrieve and select the BID pattern and targeted step. During the retrieval, finding the best match for the inputted source/application is prioritized. If an exact match is not found, the tool outputs the closest match based on semantic similarity. The Source button indicates a solution-driven design, while the Application button indicates a problem-driven design. The lower part is the display section, which displays the results in a semantic network structure. The legend section on the right side introduces the data flow, current step, and some other prompt pages(e.g. indicating result is not an exact match). The results of AskNatureNet are given in a semantic network structure, consisting of several links (S-B-A or A-B-S). To distinguish different kinds of nodes, ‘source’ nodes are displayed in green, benefits’ nodes in blue and ‘application’ nodes in grey. The gradation of color varies for different steps. Edges are displayed in solid lines between related nodes and dash lines between potential nodes. If the designer has difficulty understanding the meaning of the keywords in the node, they can click on the node to see the details and links to the original website of this keyword. Finally, for the case where the original word is not found in the semantic network, we apply a semantic similarity algorithm to find the node with the highest semantic similarity to the original word to replace the original word.

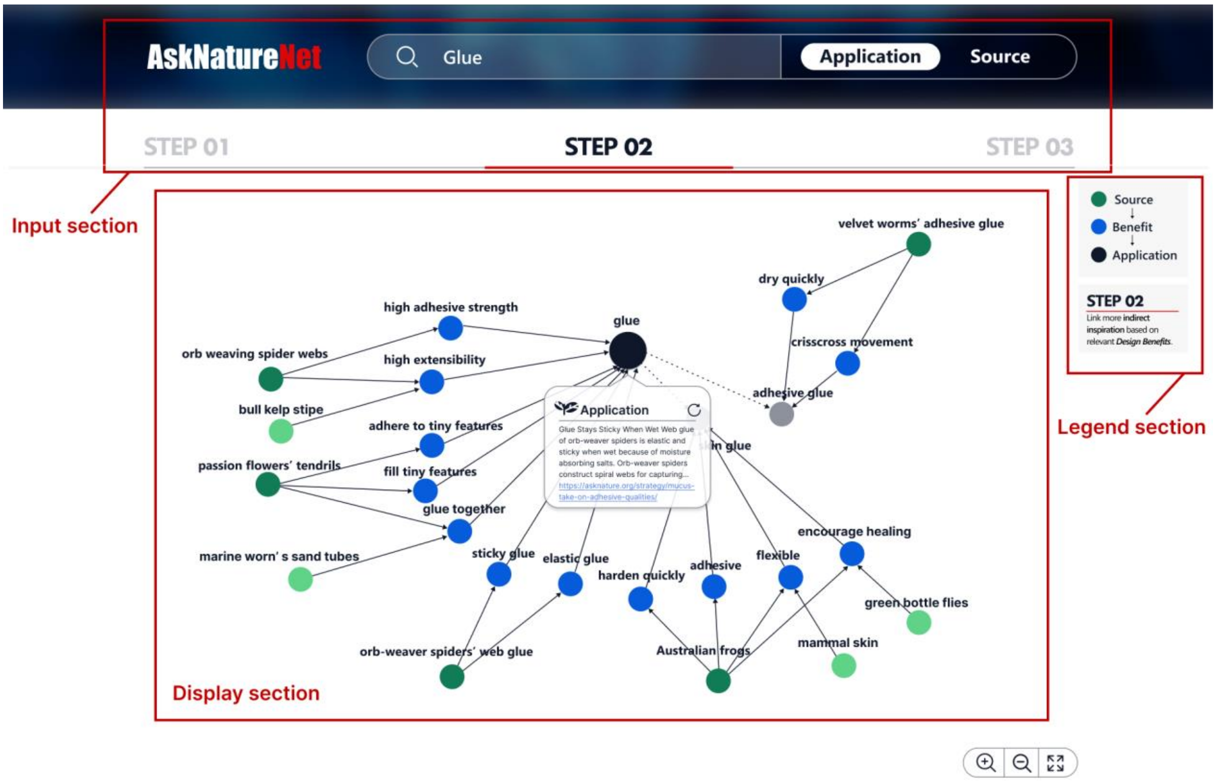

Figure 2. Functional interface of AskNatureNet

4.2 Design cases

A designer was recruited to conduct two design cases to illustrate how the knowledge-based BID approach could assist designers with problem-driven and solution-based bionic design using AskNatureNet. Generally, for the solution-driven design, the designer initially had a ‘source’ and was asked to apply the ‘source’ -> ‘benefits’ -> ‘application’ (S-B-A) link in AskNatureNet to freely

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explore the biological properties and bionic applications of the ‘source.’ For problem-driven design, the designer initially had a specific ‘application’ and was asked to freely search related keywords in the ‘application’ by applying the ‘application’ -> ‘benefits’ -> ‘source’ (A-B-S) link in AskNatureNet. For problem-driven design, surgical robot arms require high flexibility, precision and tight temperature control but there are technical barriers and industrial monopolies in the market. Thus, ‘robot arms,’ as an application area where innovation from designers is urgently needed, was chosen as the ‘application.’ The designer used AskNatureNet to obtain the A-B-S link in STEP 01, which is directly relevant to the input word. Then, in STEP 02 and STEP 03, more inspiration prompts were obtained based on the related and potential nodes. After the initial exploration of AskNatureNet, the designer gained some inspiration prompts from nature. The example of retrieved nodes is shown in Figure 3-a. At the same time, the designer could click on the nodes to explore keywords of interest that appear in AskNatureNet.

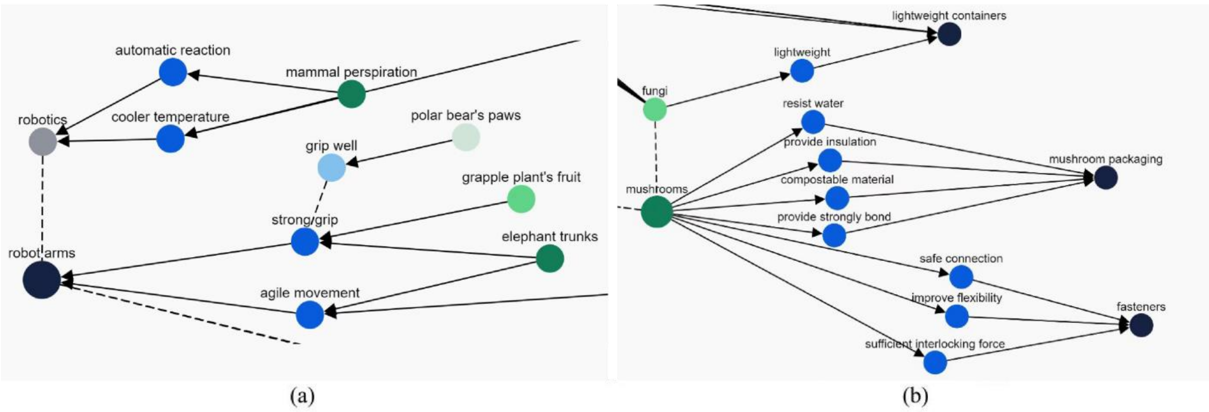

Figure 3. Examples for retrieved nodes: (a) Results for ‘robot arms’ in STEP 03; (b) Results for ‘mushrooms’ in STEP 01

Results for designer formed ‘BID ideation links’ are shown in Figure 4-a recording inspiring biological keywords in the semantic network. Starting from the design problem of surgical robot arms, the designer obtained the direct A-B-S links by searching ‘robot arms’ in STEP01: ‘robot arms’ -> ‘strong grip,’ ‘agile movement’ -> ‘elephant trunks’ and ‘robotics’ -> ‘cooler temperature,’ ‘automatic reaction’ -> ‘mammal perspiration.’ The closely spaced muscle structure of the elephant’s trunk inspired the designer to apply it to the moving part for flexible movement and fine manipulation. The mammal heat dissipation mechanism prompted the designer to use evaporation and heat absorption to prevent the machine from overheating. In further divergent thinking, the designers went on to get more A-B-S links in STEP 02 and STEP 03 that could inspire the design: ‘robot arms’ -> ‘strong grip’ -> “grapple plant’s fruit” (STEP 02) and ‘robot arms’ -> ‘grip well’ -> “polar bear’s paws” (STEP 03). The structure of the grapple plant’s fruit can be used in the gripping part of the surgical robot to improve the gripping strength. The polar bear’s rough paw inspired the designer to improve the reliability of the gripper by treating its surface. As shown in Figure 5, the designer integrated the above design ideas to form the final design case.

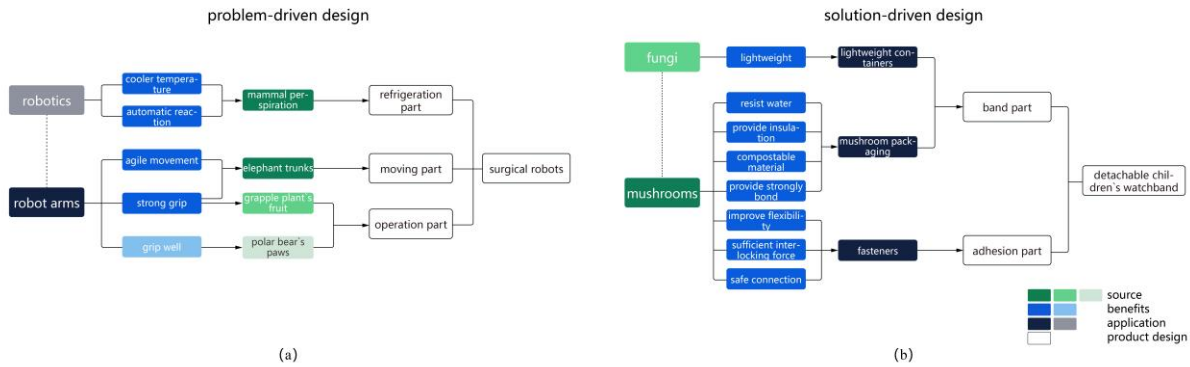

Figure 4. Examples of ‘BID ideation link’: (a) ‘BID ideation link’ for problem-driven design; (b) ‘BID ideation link’ for solution-driven design

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For solution-driven design, the designer was asked to design a product inspired by the biological strategies of mushrooms and to record the strategies used. Firstly, the designer entered ‘mushrooms’ as the input ‘source,’ and the rest tool operation steps are the same as the problem-driven design. The example of retrieved nodes is shown in Figure 3-b.

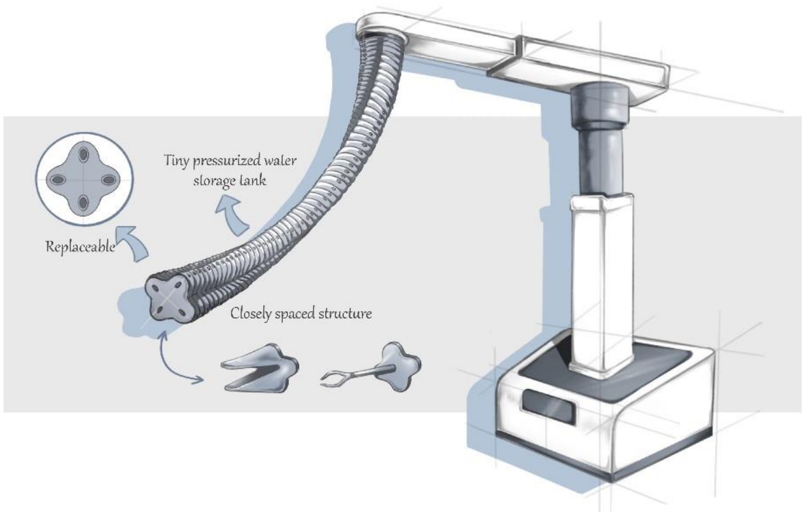

Figure 5. Sketch of the surgical robot inspired by ‘elephant trunks,’ ‘mammal perspiration,’ “grapple plant’s fruit” and “polar bear’s paws

Then, the designer wrote down all the inspiring keywords and formed ‘BID ideation link’ (Figure 4-b). Based on the design solution of mushrooms, the designer obtained the S-B-A links in STEP 01: ‘mushrooms’ - ‘resist water,’ ‘provide insulation,’ ‘compostable material,’ ‘provide strong bond’ - ‘mushroom packaging’ and ‘mushrooms’ - ‘improve flexibility,’ ‘sufficient interlocking force,’ ‘safe connection’ - ‘fasteners.’ Among them, the lightness and biodegradability of the mycelium material and the safety of the mushroom head structure fastener inspired the designers to use them in products that need to be lightweight, safe and changed frequently. Most of the existing children’s watches on the market are one-piece watches with silicone plastic straps, and the hook and loop adhesive part often scratches clothing. Therefore, the designer used lightweight, biodegradable, waterproof and heat-insulating mycelium as the strap material to reduce the weight burden on children’s wrists and the environmental hazards. At the same time, the designer was inspired by the structure of the mushroom head fastener and imitated its structure to make Velcro, which achieves a safe connection without irritating children’s skin while ensuring sufficient bite force. The final design is shown in Figure 6.

In summary, the designer used AskNatureNet to complete problem-driven and solution-driven BID, respectively. In solution-driven BID, the designer obtained inspiration for the open-ended design using AskNatureNet’s STEP 01 function. He designed a detachable children’s strap by combining two mushroom properties generated by the STEP 01 function: lightweight, environmentally friendly mycelium material and a detachable structure based on the mushroom head. In problem-driven BID, the designer considered the surgical arm the design object. After using STEP 01 for direct inspiration and STEP 02, STEP 03 for divergent thinking, the designer utilized an elephant trunk-inspired arm structure and a mammalian sweating-inspired cooling system to achieve a surgical arm that is both flexible and temperature manageable. In both cases, designers can efficiently acquire highly relevant and valuable inspiration by simply entering the right words and selecting the pattern of the BID. If the result of the STEP 01 function is not enough to complete a satisfying idea, the designer can obtain more bionic links through the STEP 02 function and STEP 03 function to help divergent thinking and associative ideation. In conclusion, the two design cases demonstrate the process of applying AskNatureNet for design creativity, and provide indication of the potential benefits of the tool. The case studies are a starting point for exploring the potential of the tool, more comprehensive research is needed to fully understand its usefulness.

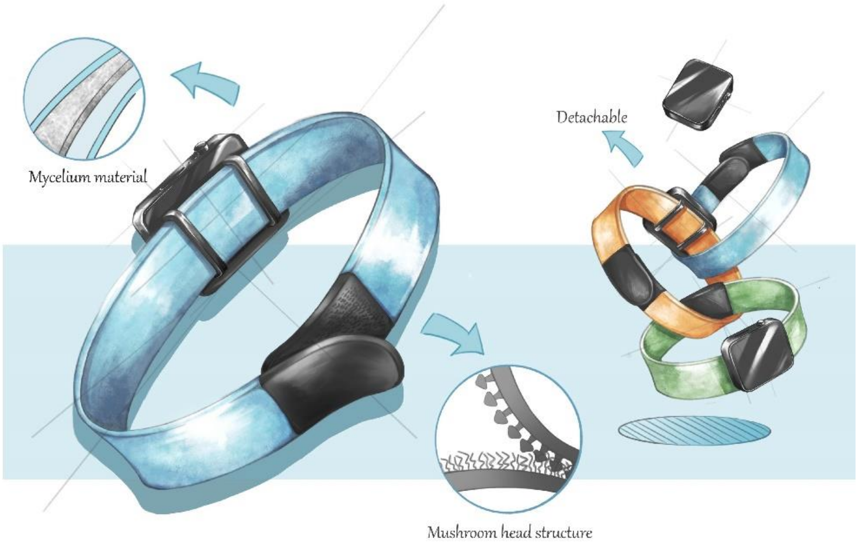

Figure 6. Sketch for the detachable children's watchband inspired by 'mushroom packaging' and 'fasteners'

5 CONCLUSION

This study presents a knowledge-based approach for bio-inspired design (BID) ideation, aimed at overcoming the limitations of existing BID tool: Existing unstructured data and models limit the ability of designers to efficiently comprehend bionic design; current BID ideation approaches only support one-way bionic information retrieval; the lack of algorithms that support ideation in BID. Our approach proposes the use of structured data to build a bionic semantic network that supports bidirectional information retrieval and developed algorithms to enable divergent thinking in BID. This approach is implemented as a BID tool called AskNatureNet.

The main contributions of this study are:

1. A method to extract bio-design cases into structured data
2. The construction of a semantic network based on the structured data to support bidirectional BID retrieval
3. Development of a divergent retrieval method for ideation inspiration

The process of the knowledge-based BID ideation approach was demonstrated through two design cases in which the designer used AskNatureNet to generate solutions for a detachable children's strap inspired by mushrooms and a surgical arm combining the features of an elephant trunk and mammalian sweat glands. The results showed that AskNatureNet could be applied to both solution-driven and problem-driven BID processes.

The BID approach presented here offers implications for fitting into the real-world BID process. The extraction of bio-design-cases and organization of knowledge into the S-A-B structure is the analogy encoding process, which involves the storage and organization of information about source analogies. The two patterns of BID and the retrieval method for ideation, support the analogy retrieval and mapping process. The results of the case studies suggest that the AskNatureNet tool has the potential to support designers in generating innovative and novel solutions through bio-inspired design. While the case studies provide some preliminary evidence of the tool's potential, more evidence is necessary to make definitive conclusions about its usefulness. Although AskNature is one of largest BID data source, it still cannot cover all BID design fields. To improve its practical use and ideation outcomes, future work will focus on expanding and fusing the other heterogeneous data.

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