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Research paper

Biomimicry – Core Stages, Design Process, and Gaps

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Abstract

Nature is a world-scale R&D in a laboratory called the universe. Some of the best inventions and innovations are actually built based on nature's design. But in order to wield the power of nature's design, one must first learn about the three core stages of biomimicry: *Search*, *Abstract*, and *Transfer*. One must also know the steps of designing with biomimicry, either problem-driven or solution-based design process. Since Theory of Inventive Principles (TRIZ) is known as the most promising tool to bridge the biology-engineering gap, this paper presented both problem-driven and solution based design process with TRIZ cycle. There had been many biomimicry tools emerging since 1987, but tuning and refinements are still required. The biology-engineering gap is still far from being bridged. This paper presented some of the ideas of potential approaches in bridging the biology-engineering gap; TRIZ, Function-Behaviour-Structure (FBS) modelling, and pattern language.

Keywords: *Bio-inspired design; Biomimicry; Function-Behaviour-Structure; Pattern language; TRIZ*

1. Introduction

In the beginning God created the heavens and the earth. Since then, nature had been constantly transforming and adapting to the threats encountered in order to survive and thrive. Nature has been on an ongoing research and development process in finding solutions to different engineering challenges, from the range of nano to macro, a single cell to an entire ecosystem [1]. Various knowledge from nature had been successfully transferred into technology as in railway industry [2, 3], architectural design [4], [5], tissue engineering [6], water treatment [7], drug delivery system [8], engineering tools [9], and also in optimizing the organization of companies [10]. These are known as bio-inspired design (BID).

The term "bio" means life and "mimetic" means an aptitude for mimicry. Biomimetic aims to understand successful strategies adopted by nature to counter human problems [11]. Biomimicry is not a new concept, since the term "biomimetics" was first introduced by Otto Herbert Schmitt in 1969, but it is gaining popularity in recent years [12]. Gebeshuber, Gruber, and Drack had predicted that by the year 2059, biomimetics will be contributing in addressing the 15 global challenges [13]: sustainable development, water, population and resources, democratization, long-term perspectives, information technology, rich-poor gap, health, capacity to decide, peace and conflict, status of women, transnational crime, energy, science and technology, and global ethics.

Nature is a rich source of knowledge and inspiration of inventions as nature itself is an enormous collection of inventions that overcame the test of practicality and durability. However, engineers lack the knowledge of biology. Biology is about describing and classifying nature's behaviours while engineering is more decisive and generates rules and regulations [14]. This had made the adaptation process in BID difficult as they do not know how to extract or where to find these inspirations from. Furthermore, engineering is the application of knowledge explored by scientists and mathematicians, while in the context of biomimicry, the knowledge explored by zoologists, ecologist, botanist, entomologists, and any other branches of biologist. A most common example of biomimetics is the *Shinkansen*. Chief engineer of the *Shinkansen*, *Eiji Nakatsu* saw a kingfisher dives through two mediums of different density quietly. He then transferred the working principles of the kingfisher to the nose of the *Shinkansen 500* Series to reduce sonic boom caused by high pressure at the train nose when entering and/or leaving a tunnel [15]. If a proper bridge is able to bridge the gap between the engineering world and this biological database of nature, an abundance information of invention and innovation could flow through directly into the engineering world, as if breath of life is blown into technology.

The good news is that there were 43 design tools available since 1987 until 2015 to support biomimicry, while most design tools are only available since 2014 [16]. But the bad news is that all of these tools are still far from perfect. Without a good and proper tool assisting designers to create BID products, designers tend to make common mistakes which complicate the process of biomimicry and causing a divergence of results instead of converging to one. Helms, Vattam, and Goel identified eight errors that were commonly encountered by most designers [17]:

i. Vaguely defined problems.
ii. Poor problem-solution pairing.
iii. Oversimplification of complex functions.
iv. Using "off-the-shelf" biological solutions.
v. Simplification of optimization problems.
vi. Solution fixation.

vii. Misapplied analogy.
viii. Improper analogical transfer.

In this section, the issues faced by engineers in attempt to use biomimicry in designing was briefly presented. **Section 2** will present the core stages of biomimicry. **Section 3** will present the design process of biomimetics. **Section 4** will present some other potential approaches to bridge the biology-engineering gap.

2. Biomimicry core stages

There are three core stages in biomimetics design process; *Search*, *Abstract*, and *Transfer*. These three stages are also the foundation to define a biomimetics product, as part of the ISO standardization initiative that is based on VDI Guideline 6220 [18]. Based on the report by Wanieck, Fayemi, Maranzana, Zollfrank, and Jacobs, there are 21 tools that assist designers to search for biological system, 19 tools to abstract both the problem and the biological solution, and 25 tools supporting transfer from biology to technology and vice versa [16].

2.1. Search

The search can be performed in a wide range of hierarchical levels; molecule, organelle, cell, tissue, organ, organ system, organism, population, community, ecosystem, and biosphere [19]. Truly for an engineer to search for a biological system that meets the need of an engineering problem from nature is equivalent to finding a needle from the ocean as there are unlimited possibilities. In addition to that, engineers only have limited knowledge on biology. Therefore it is crucial to have search tools based on thesauri, ontologies, and taxonomy to fill in the knowledge gap that the engineers are facing. There are four different ways to search for biological systems [17]:

i. *Change constraints:* If the problem is vaguely defined, such as ‘climbing’, change the constraints, for instance ‘adhere’ to increase the search range.
ii. *Champion adapters:* Search for a biological system that survives in most extreme case. For instance, for ‘climbing’, search for animals which are able to climb even on smooth surfaces.
iii. *Variation within a solution family:* Various biological systems resolve the problem in different approach, such as gecko has microscopic hairs under its feet which allow climbing, rats have sharp claws to climb smooth surface, snails has mucus under its foot to climb on any surface, etc.
iv. *Multi-functionality:* Search for biological systems that solve multiple problems simultaneously with a solution.

Having less knowledge on biological systems is a fact that all engineers cannot deny. In order to bridge this language gap between engineering and biology, Nagel, Stone, and Mcadams developed an Engineering-to-Biology Thesaurus, which correlates biological terms to engineering based on the functional basis [20]. After being able to translate the keywords, engineers can now search for functions and/or structures of desired biological systems via available ontology databases on the internet such as Synapse [21] and AskNature [22].

Unlike ontology which classifies information according to a limited functional group, Natural-Language [23] takes advantage of biological information from existing and available texts by searching directly with keywords for relevant phenomena. Designer can search with a query keyword for a related analogy and implement the analogy to the problem. However, the development of natural-language based on text is highly dependent on the quality of the text. The more specific the context, the more technical terms will be found in the text which will most probably be beyond comprehension. Furthermore, the search for relevant analogy is subject to the query keyword of the user [19]. When the search result is highly dependent on the query keyword, there will be a tendency where irrelevant results are suggested as well because one of the biggest problem faced with current search tools is that the user is unable to clearly provide a query keyword that expresses the desired contents [24]. Therefore, the biomimetics image retrieval platform from “View Search Hokkaido” project is developed [25]. This platform provides 2D scanning electron microscope (SEM) images, sorted in structural groups, and allows its user to search with either images or query keywords. Since the image of structures provided in this image retrieval platform is at a microscopic level, the solution may have a risk of failing if scaled to a bigger size. For instance, geckos are able to climb on smooth surfaces because of the Vann Der Waals, intermolecular attractive forces, exerted by the microscopic hairs under its feet. If scaled up to a huge size, there will not be any intermolecular forces anymore.

There is still a lacking in image search tool and there is a need for such tool to support the search process. Without a proper search tool, finding a solution to produce a bio-inspired design will be as difficult as Greek to the engineers.

2.2. Abstract

In biomimicry, the abstraction stage is the most important as well as the most difficult step [26]. In this stage the biomechanics and functional morphology of a biological system is first analysed. Then, quantitative analysis is performed in order to obtain the detailed understanding of the biological structures, shapes or behaviours, and functions. In other words, the solutions are separated from their natural examples. It is from these knowledge that the design solutions are abstracted from.

There are numerous abstraction tools which are very effective in filtering and presenting information based on its significance to the problem, and are able to model complex systems in a generic manner yet retaining the specific constraints, such as BioTRIZ [14], the complete viable system model [27], and SAPPhIRE model of causality [28, 29].

BioTRIZ by Vincent is an abstraction tool where the working principles are exactly the same as TRIZ, but in a biological context. BioTRIZ operates just like the conventional TRIZ by Altshuller, which has a set of guided steps for a converging solution. BioTRIZ also had a database of biological solution sorted out according to the Inventive Principle combinations. However, developing the database for this biological solution, even only for one solution, requires a lot of time and resources. Furthermore, [30] himself stated that BioTRIZ did not manage to marry biology with engineering as it fail to derive the basic rules of biomimetics.

The Complete Viable System Model of Structure-Function Pattern approach, Figure 1, is a hybrid model of S-Field modelling and the Law of System Completeness, originating from TRIZ. Helfman Cohen, Reich, and Greenberg developed this tool to identify structure-function patterns [27]. The model identifies the main function and related structure of biological systems as part of a complete systems model, in relation to the energy sources in space. This model is able to provide a functional model of biological systems and explain the role of the working structures within a complete system that performs the main function.

There are also some abstraction tools which are computational software such as Design by Analogy to Nature Engine (DANE) [31] and Idea-Inspire [28]. Professor Amaresh Chakrabarti and his research group analysed over 1200 movements for both natural and artificial system to develop the databases of Idea-Inspire. It is the first searchable computer repository of biological systems and biological inspired design. In the latest version, Idea-Inspire 3.0 [32] is now a web-based tool. Idea-Inspire acts as an ideation stimuli to its user in problem solving. Idea Inspire 3.0 has novel features for supporting understanding, ideation, synthesis and expansion of its knowledge base. However, this tool is currently still undergoing preliminary testing and unavailable publicly yet.

DANE is an interactive knowledge-based design environment which provides the user access of a library containing Function-Behaviour-Structure (FBS) models of natural and artificial systems. This tool assists development of biological inspired design by helping designers to find relevant biological systems, understanding the functioning biological system, and construct FBS models. Its library has about 40 FBS models. DANE is nowhere as neat as Idea-Inspire because there are numerous issues concerning its credibility as the library is small and limited. Some student-

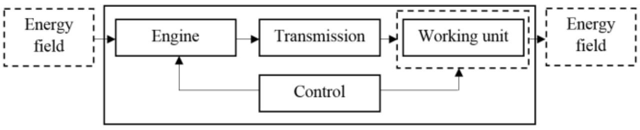

Fig. 1: The Complete Viable System Model (dashed line represents elements of S-Field, solid line represents elements from the Law of System Completeness) [27].

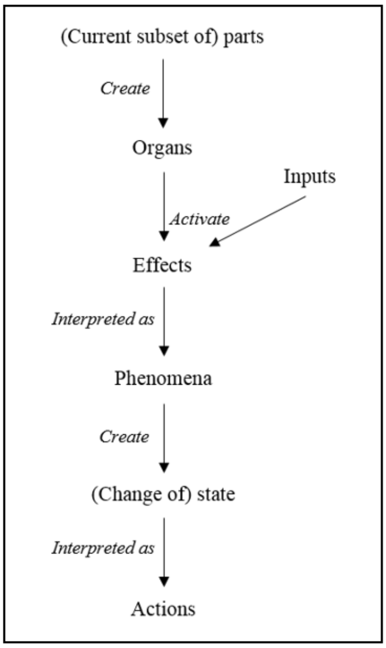

Fig. 2: SAPPhIRE model of causality [29].

developed FBS models are incomplete and of low quality.

SAPPhIRE model of causality is also a FBS model framework. Professor Amaresh Chakrabarti built and used SAPPhIRE to build the databases of Idea-Inspire. In SAPPhIRE, the system's function must be intentional and is superior to the system's behaviour. The behaviour can be taken as how the function is performed. Structure is described by the elements and interfaces of which the system and its direct environment interacting with. SAPPhIRE comprises of seven constructs; State-Action-Part-Phenomenon-Input-oRgan-Effect. The constructs are first defined in 2005 but it is suggested by other researchers and designers that it is difficult to understand the model [28]. Therefore, Srinivasan and Chakrabarti redefined the constructs with well-defined terms [29].

i. *Phenomenon:* An interaction between a system and its environment.
ii. *Effect:* A principle that governs an interaction.
iii. *State:* A property at an instant of time of a system or an environment that is involved in an interaction between a system and environment.
iv. *Action:* An abstract description of an interaction between a system and its environment.
v. *Input:* A physical variable (material, energy or information) from beyond the system boundary which triggers an interaction between a system and its environment. This variable activates the governing principle.
vi. *Organ:* A set of conditions and properties of a system and its environment needed for an interaction between them. These are also needed to activate the effect and remain unchanged during an interaction.
vii. *Parts:* A set of physical components and interfaces that form the system and its environment.

The constructs are related to one another in a cause-and-effect relationship as shown in Figure 2. Srinivasan and Chakrabarti [29] explained it as:

The set of components and interfaces that constitute a system and its environment (parts) create a set of properties and conditions (organ). When the system and its environment are not in equilibrium, there is a transfer of a physical variable in the form of a material, energy or signal (input) across the system boundary. This physical quantity in combination with a particular set of properties and conditions, together activate a principle (effect). This principle is responsible for an interaction (phenomenon) between the system and its environment. The interaction between the system and its environment changes a property of the system (and environment) (state change). The change in property can be interpreted at a higher level of abstraction (action).

It is important for an abstraction tool to be as versatile as possible; be it in the number of user using the tool, the field it is employed in, the time required to implement it, simplicity of the tool yet presenting comprehensive information, and becoming a stand-alone tool while aiding subsequent tools as upstream support [33]. Biological knowledge is the fuel of the abstraction tool. However, the available knowledge to support the refinery and extraction of design principle is still insufficient. Therefore, more effort in biological knowledge harvesting, such as ontologies and taxonomy, is required in order to support this stage more effectively. Yet another issue arise as collecting and compiling these knowledge is a highly time-consuming effort.

2.3. Transfer

Transfer is the flow of abstracted principles from biological systems and applied to the target solution [34]. However, Fayemi, Wanieck, Zollfrank, Maranzana, and Aoussat defined the process of transfer, differently, as a process of knowledge transfer from biology to engineering and vice versa, where reframing the problem into a biological context is also considered as a transfer process [35]. Therefore, there is a contrast in the statement between [34] and [16], which Helfman Cohen claimed that there are very few transfer tool available while Wanieck claimed that there are 25 transfer tools.

Schild, Herstatt, and Lüthje identified four types of different knowledge transfer [36]: (1) Direct transfer of an existing technology into a new context, (2) transfer of structure, (3) partial transfer of functional principles, and (4) use of an analogy as idea stimulus. While Sartori, Pal, and Chakrabarti [37] identified four levels of transfer, that resembles the four types of knowledge transfer proposed by Schild, from the SAPPhIRE model; parts, organ, attributes, and state of change. At the end of the transfer stage, the designer will come across with only one unique solution and the designer will be able to have a comprehensive understanding regarding the relevant biological knowledge. The designer should also be able to completely sub-modularize the generated solutions in order to enhance versatility [33].

3. Biomimetics design process

There are many approaches of problem-driven design process for biomimicry. Fayemi et al. [35] reported a detailed review on all sorts of problem-driven design process since year 2004 to 2015. One of the popular design process is the double TRIZ cycle, introduced by [38].

3.1. Problem-driven biomimetics design process

Figure 3 shows the double TRIZ cycle the author adapted from [33]. The cycle shows that a specific technical problem is first generalized and search for a solution from biology. After acquiring the solution needed, the generalized solution is then used to address the specific technical problem as a specific solution.

The problem-driven biomimetics design process begins with a need and a demand from the society. This demand is translated to a technical problem and then converted into a biological problem, which then proceeds to search for a biological solution and convert it into a technical solution. A technical problem is the main engineering problem and function that designers want to solve and achieve. The problem and function are to be specific and must be clearly clarified. In this stage, the designer asks *"what's the job?"* Taking an insulation mug as an example, the main problem of a mug is heat loss via conduction, convection, and radiation [39] while the function of the mug is to retain heat of the fluid stored.

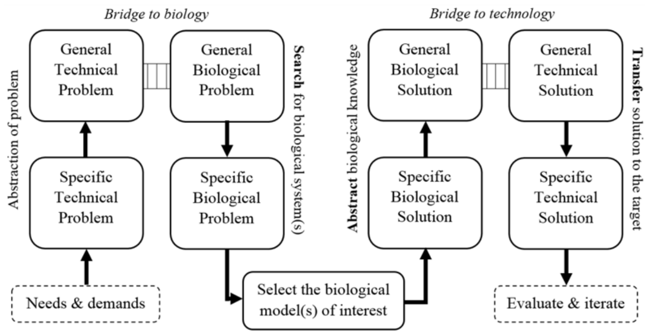

Fig. 3: Problem-driven biomimetics design process with double TRIZ cycle [33, 34, 38]

The abstraction of the main problem generalizes and decomposes the problem into sub-problems [19, 40]. Every systems have subsystems, including problem and function. From these sub-problems, the designer will be able to identify the main mechanisms that is able to do the job. The designer then select the part(s) that requires nature's strategy to get the job done. In this stage, the designer now asks *"what contributes in getting the job done?"* and *"which part requires nature's solution?"* The sub-problems of the example will be heat insulation mechanism, and heat insulant. In this example, heat insulation mechanism will be taken as the problem of interest.

Here comes the crucial moment, where bridging technology to biology begins. The sub-problem is reframed into a general problem in biological context. Bridging to biology is crucial as the problem functions, requirements and conditions must be clearly defined before being able to know what source to search for. The designer need to ask *"did nature face this problem too?"* and the answer to that question is obviously *"YES!"* Using the same example, the problem of interest is the heat insulation mechanism. The designer will need to identify related problems in nature such as 'animals keeping warm in arctic condition', 'animals keeping cool in the desert', or 'plants surviving in the desert'.

Next, the designer will need to specifically search for biological systems based on the descriptions of the general biological problems. The designer will now scratches his head and asks *"what biological system(s) can overcame this problem?"* The designer now need to search for biological systems that survived critical temperature such as polar bear and emperor penguin keeping warm in arctic condition, skipjack tuna not freezing under the Atlantic Ocean, toucan keeping body temperature low, termites keeping nest temperature cool underground, etc.

After having a list of potential biological systems, the designer will now starts asking himself *"which biological system to choose?"* and the answer to that question is *"whichever systems that do the job – within the context – with the easiest method."* At this stage, a loud *"WOW!"* will most probably be heard as the designer find out *"how did it do it?"* Polar bear keeps warm with its fur coat [41], emperor penguins keep warm by huddling groups [42], skipjack tuna keeps warm with counter-current heat exchanger [43], toucan regulates body temperature by blood flow regulations at the bill [44], and termite mound remains cool with hollow porous structure [45]. The polar bear seems to be a potential solution analogy. The designer is already in the 'specific biological solution' step, abstracting the biological knowledge.

After finding sufficient sources of inspiration and knowledge, these biological solutions will then be abstracted and generalized to identify the working principles – patterns. The designer now need to ask *"what is the pattern from all these solution?"* The polar bear fur is long, transparent, and hollow, which scatters sunlight and at the same time reflects infrared generated from the body. The surface of the skin is darkly pigmented which retains absorbed sunlight and bodily warmth. There is only one biological system selected in this example, however, the pattern is still extractable. The pattern in solving this problem is hollow translucent fur and black pigmented skin [41].

Reaching to the second bridge, the bridge of biology-to-technology, the designer will need to "technologize" the biological patterns. Now the designer need to ask *"how does this work in engineering?"* From the previous step, the pattern extracted is hollow translucent fur and black pigmented skin. The hollow translucent fur can be replaced with hollow translucent fabric while the black pigmented skin can be replaced with a black temperature-resistant coating [41].

Finally, transfer the general technical solution extracted to the target as specific technical solution. The solution will now be modified to suit the original sub-problems abstracted from 'general technical problem' step. Now the designer will need to ask the crucial question, *"how can this solution fit into the context perfectly?"* First, the inner layer of the mug must be made of heat-resistant material with black coating on the outer surface. Then, a translucent heat-resistant container of bigger size is then used to surround the mug creating a column of empty space in between. Finally, translucent hollow tubes of heat-absorbent is inserted into the empty space creating air pockets within and between the tubes. If any heat managed to radiate out from the black surface will be reflected back by the translucent surface and trapped within the tube region and radiate the heat back to the black surface, keeping the fluid within the mug hot.

The designer now come to the '*eureka*' moment where one sub-problem had been solved. Coming to the end of the design process, the concept must now be evaluated by iteration. The term 'iterate' doesn't mean that the design needed to be optimized by a set of algorithm with a software. It simply means repeat the steps done after the evaluation based on the evaluation criteria. The designer will now need to ask the ultimate questions; *"Is the analogy correct? Is the abstracted model suitable? Is the biological system effective in this context?"* If the objective is vaguely defined, the solution may not be able to solve the actual problem. The problem definition then need to be refined again. The mechanism of the insulation mug is now solved. But the heat-resistant material is still unknown. The designer can either use a commercial heat-resistant material or iterate from 'general biological problem' for a material from nature that resist heat. After solving all of the sub-problems, the concept is then passed on to the next stage.

3.2. Solution-based biomimetics design process

The solution-based biomimetics design process are slightly different from problem-driven design process, as shown in Figure 4, as the search for biological system is already done in the first step. It is relatively simple compared to problem-driven design process. The designer first had a biological encounter before having a problem definition. Helfman Cohen and Reich called this the "Bio-WOW" moment [34]. Helfman Cohen suggested that the problem is first defined before abstracting the principles. Therefore, the biological solution should first be defined by asking *"how did it do it?"* and then extract the working principles enabling the biological solution as it is done by [46] and reviewed by [19]. For this example, the encounter with polar bear will be taken as the Bio-WOW moment. After abstracting the biological knowledge, the designer now know how a polar bear keeps itself warm in the North Pole. Next, the designer finds the general pattern of the mechanism, which is hollow translucent fur and black pigmented skin.

Bridging to technology, the search for a general technical problem begins. The designer will now ask "what can this new-found biological solution contribute to technology?" The designer will most probably come across numerous general applications

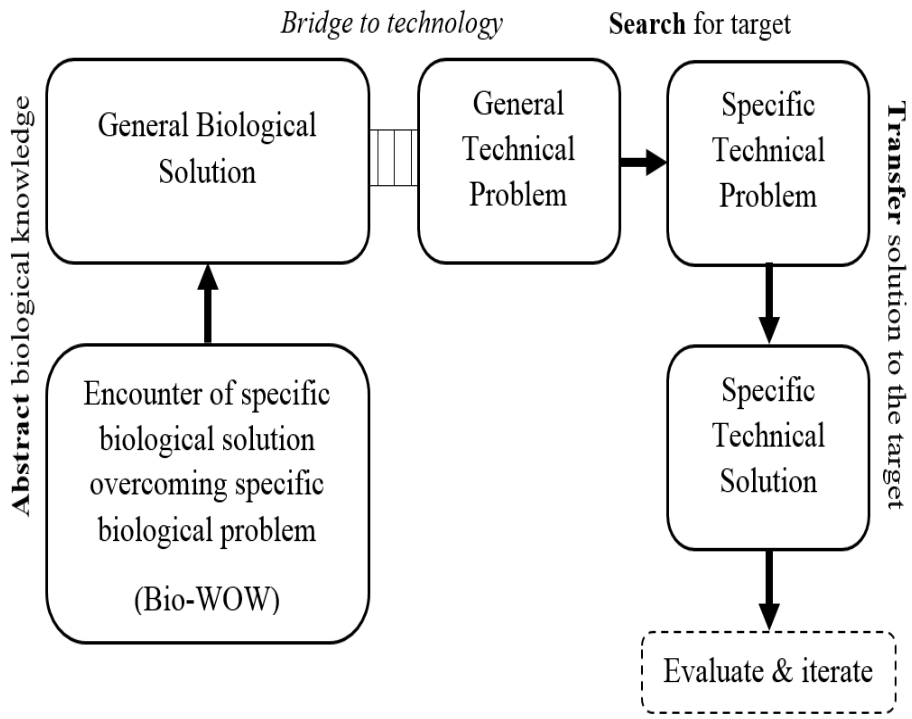

Fig. 4: Solution-based biomimetics design process with TRIZ cycle [34], [46]

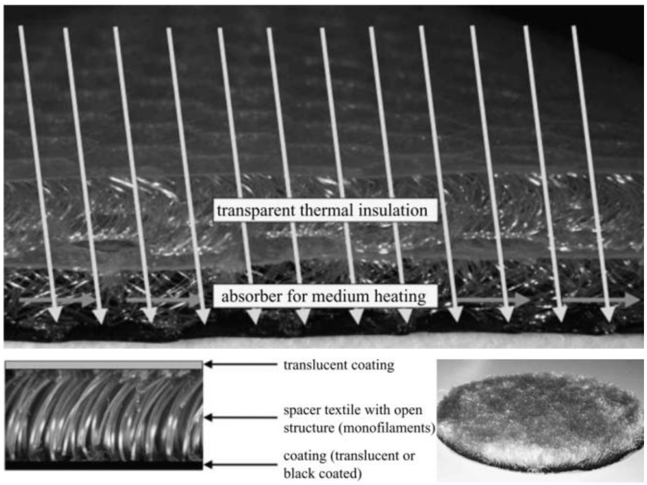

Fig. 5: Thermal insulation textile composites [41].

with the new-found biological solution such as 'keeping warm', 'keeping cool', 'heat absorbent', 'light scattering', 'camouflage', 'heat reflection', and the list goes on and on. These general applications may look familiar because these are actually sub-functions of some unknown specific problems.

In searching for a specific technical problem, the problem definition must be specified, as well as the conditions and requirements. Let's assume that the designer is interested in designing a thermo-camouflage armour for military use. In dark, soldiers use thermal goggles to observe in-coming enemies. The problem and function will be 'getting spotted by enemy' and 'thermal camouflage', respectively, while the sub-functions will be camouflage and heat reflection.

The solution will then be transferred to the target application or concept. The designer now need to ask "how can this solution fit into the context perfectly?" First, the bottom layer of the armour must be darkly-pigmented and a good heat insulant. Then, the armour will be covered with translucent spacer textile of good heat absorbent. Finally, a layer of translucent coating is used as the outer layer of the fabric. This textile, as shown in Figure 5, has the advantage of high mechanical stability, high thermal stability, flexibility, deep drawability, and chemical resistance [41].

Coming to the '*eureka*' moment, the designer will still need to ask the ultimate questions; *"Is the analogy correct? Is the abstracted model suitable?"* Noticed that the biological system is not evaluated in this approach because this is a solution-based process and the biological system *is* the solution. Instead, it is the understanding and knowledge of the designer regarding the solution is being evaluated.

4. Potential biomimetics approaches

As mentioned in **Section 1**, there were 43 design tools available since 1987 until 2015 but none is able to perfectly bridge the biology-engineering gap. However, there are some approaches which can be used in attempt of bridging this gap. Some of these approaches were already widely being used and are very prominent, while some are being left behind, though it has great potential.

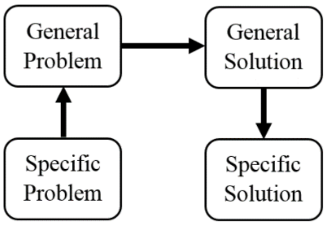

Fig. 6: Summary of TRIZ process of problem solving [33].

4.1. TRIZ

According to Professor Julian Vincent, the most promising tools that could use to facilitate the bridge is TRIZ (*Teoriya Resheniya Izobretatelskikh Zadach*) translated as the Theory of Inventive Problem Solving, TIPS [14, 34, 47–49]. TRIZ is an analysis and forecasting tool used in solving inventive problem which was derived from patents of invention by Genrich Altshuller. It is a method which pushes a system towards its ideal state, semantically. TRIZ is a powerful methodology with practical sets of tools for inventing and solving technical problems easily and rapidly. With TRIZ, successful transfer of various inventive solutions among different fields of engineering is made possible. As TRIZ was derived from patents of inventions, it separates the problem from the original context, as shown in Figure 6, and search for a solution from a wide range of knowledge of science and technology. This is essential because designers tend to have biases towards certain solutions when using biomimetics which will either help or hinder the process. The core of biomimetics is transferring knowledge between domains; biological system and technical system.

Biomimicry is a bridge between the two systems; the living and the non-living. Unlike biomimetics, TRIZ does not have the ability to point out biological systems and functions because it is derived from artificial and non-living technical systems. However, the principles and laws governing TRIZ are very useful in abstracting and transferring biological principles to engineering applications. Furthermore, Currie, Fung, Mazza, Wallace, and Shu [50] tested between biomimetics and TRIZ and found out that both methods are mutually inclusive in generating potential solutions as there is an overlapping area between the stimuli of the two methods. [14, 34, 48, 50, 51]

Every system is a subject to a super-system, which is the environment beyond the system, and operated by sub-systems [48]. A car is subjected to the control of the traffic rules, the condition of the road, the signal of the traffic lights, the weather, the pedestrians, etc. The car cannot operate if there is no engine to combust the fuel and produce energy, no fuel tanks to store the fuels, and no wheels to produce traction. Sub-systems are all interconnected with one another within the boundary of the system. Simply varying one component will be able to cause tremendous changes to the system and even to the super-system. Therefore it is necessary to always consider the interactions of a technical system with the systems above and below it. System Operator, or 9-Windows [52], of TRIZ is created for this purpose, to analyse the system in terms of SPACE and TIME. The system is not only analysed with the sub-systems and super-systems, but also the states of the system in the past, in the present, and in the future. System Operator will be a very good abstraction tool when it comes to abstracting natural phenomena where every small and discrete details will be analysed.

Throughout the lifetime of a technical system, the system will evolve in eight different patterns [53, 54]:

i. Life cycle
ii. Dynamization
iii. Multiple cycle (transition to bi-system or poly-system)
iv. Transition from macro to micro level
v. Synchronization
vi. Scaling up or down
vii. Uneven development of parts
viii. Replacement of human (automation)

The evolution process of these technical systems is highly dependent on the Law of Ideality. Every technical contradiction removed is an evolution of a technical system nearer to its ideal state. This is why TRIZ users is able to claim that TRIZ is a methodology which can nudge a system closer and closer to its ideal state [54]. According to this law, any technical system has the tendency to become more and more ideal throughout its lifetime. Ideality encourages problem solvers to think from the Ideal Final Result (IFR) instead of focusing on the problems, then removing the barriers between reality and ideality. The Ideal Machine, or IFR, determines the direction of the search as it reveals the ideal condition desired. When formulating the IFR, avoid any forms of psychological barriers [55].

The key of invention is to remove barriers towards ideality. Whenever a technical contradiction is removed, the technical system became more ideal. Therefore, an invention can be judged by its degree of ideality. When it reaches its ideal state, the mechanism will completely disappear, yet the job is done. This is when the idea of “Self-X” emerges, where everything is self-sustaining [55, 56]. It requires lesser input but produces a higher rate of output. In other words, increasing benefits and reducing costs. In simple terms, IFR is the ideal solution which contains all of the benefits and without any costs needed nor producing any harms.

This law is also found in nature where a balanced ecosystem is prove to it. Nature is a closed-loop system where wastes from one system are recycled as beneficial input to another system, which will produce some beneficial by-products. For instance, a fallen branch from a tree will be a meal to the termites. The over-populated termite colony will be a meal to the anteater. The waste product of the anteater will be a nesting place to the dung beetle. The dead beetle will be feasted by various arthropods. These arthropods also feeds on animal waste products and decaying plants and turns these waste into useful soil and also fertilizers to the surrounding plants. Imagine this closed-loop system is also adapted into linear economy industry, especially manufacturing and production, waste and pollution will no longer be an issue because all these wastes will be channelled to somewhere else and be beneficial [57]. This is *ideality*!

Another very effective method that TRIZ uses in illustrating complex problem, besides System Operator, is the Substance and Field analysis (S-Field). According to this model, a function is defined as an interaction between two substances and one field [58]. S-Field describes how a substance (S1) interacts with another substance (S2) with the present of a field (F) in order to perform a certain function. S-Field Model (SFM) is a model of minimal, functioning, and controllable technical system. SFM only shows the conflicts and interactions of substances and fields. But if SFM is to be used to describe an actual technical system, additional elements must be introduced. Classical TRIZ states that every technical system must has four essential components; *engine*, *transmission*, *working unit*, and *control unit*. If any component is missing, the technical system will cease to exist, if any components fails, the system will not “survive”. Engine converts energy, transmission unit transmits the energy, working unit performs the main function of the system, and control unit controls and guides the parameters that are altered by the function. This law, the Law of System Completeness enables the inventor to identify a given complex of components with a technical system.

TRIZ had been popularly used to build the biology-engineering bridge. Some of the tools in TRIZ such as System Operator, law of ideality, S-field, inventive principles, law of system completeness, and ARIZ. Though many of these tools had been employed in biomimicry, there are still a lot of opportunity undiscovered lies within TRIZ in terms of bridging this gap.

4.2. Function-Behaviour-Structure (FBS)

The entire ecosystem is actually a living system itself – a super-system, with many systems relating with one another inside it. The living system reacts differently and instinctively in different situations, because of the organs and their respective unique internal systems – the sub-systems, with a degree of unexpectedness which directly relates to the complexity of the living system. This gives living systems great adaptability and versatility, but at the expense of the predictability.

In terms of relating biological systems to technical systems, the Function-Behaviour-Structure (FBS) model fits this job perfectly. In order to describe the solution causally, the Function-Behaviour-Structure (FBS) model framework can be employed to describe the finest detail of a concept solution. Though FBS are widely used in computer system, it is still a useful tool which can be used to abstract biological system.

There has been many different definitions on the terms “function”, “behaviour”, and “structure”.

4.2.1. Function

Function, in semantic view, is known as the input/output (I/O) flow of energy, materials, and signal via a system [40]. Systematically, function is a description of an intended action needed to be done, regardless of how it is accomplished, and the intended purpose of a design made, which Deng classified as action function and purpose function, respectively [59–64]. But in order for a structure to accomplish its purpose, or the specified function, a physical disposition is needed [65, 66]. In Kuiper’s definition, functional description also reveals the connection in producing the behaviour of a system. This is what enables the physical disposition of structures in a system. The action function is an abstraction of intended and useful behaviour that a structure possesses. This is also supported by the definition of [67] which states function as a schema that specifies the conditions before and after a task is performed and this function schema contains a reference to the behaviour that perform the function.

Functional reasoning is crucial as it addresses the problems and solutions in terms of functional description. In biomimicry, functional reasoning allows designers to search for natural solutions to address technical problems. It is a link between what natures did in order to overcome this problem in their environment and what function should the design have to overcome this problem in our context. Technical problems that engineers face nowadays are not new to nature as nature had been adapting all these while to overcome these problems.

Functional Modelling [63] is a tool which models the functions of biological systems and then translates it to the engineering domain. Functional models take the analogies of nature and compare it to the function in technologies and then explores the similarities, differences, and analogies between the solutions at the sub-function level. Because it compares between biological functions and technical functions, this modelling technique demands a high biological function knowledge from the designer. Another tool that could assist this functional mapping process is the Engineering-to-Biology thesaurus [20] where eight different engineering functions are translated into biological terms.

4.2.2. Structure

Structure, basically, are the derived elements of a system and the relationship of these elements with the system [61, 62, 64, 67]. It consists of the properties of the artefacts, the dimensions, and geometry of these materials, and their topological relations [65]. Galle summarized it as space, material and the function between space and material [66]. An ideal machine will have no structure at all because it requires zero input to achieve maximum output. However, the ideal machine is a fantasy, thus, structures are needed to perform an action. The inputs or outputs are external factors while the functions are specific requirements. Therefore, the only

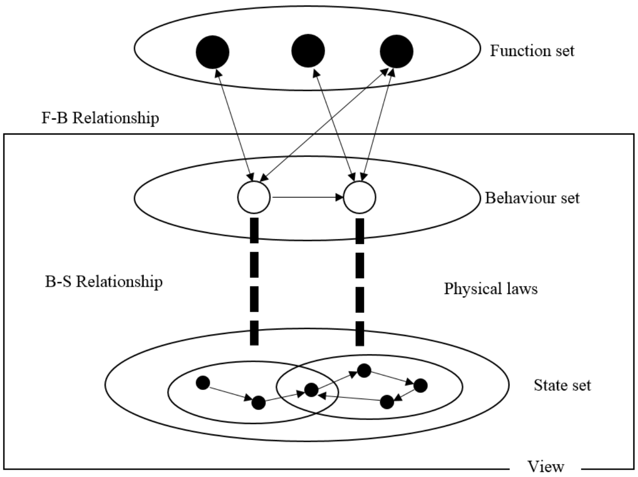

Fig. 7: Umeda's representation of relationship among Function, Behaviour, and State [68].

variable that the designer can manipulate in the design process is the structure of the device. This is where the outcome of functional modelling come into action. After discovering an analogy from biological system which is able to perform the desired function to address a technical problem, the structure of the system which enables it to perform the task will be transferred.

4.2.3. Behaviour

As function describes what should be done, behaviour describes how it should be done [59]. The most common view of behaviour is that behaviour is related to the change of state, which is the physical disposition of the structures in a system [61, 62, 65–67]. This is the Behaviour-Structure relationship. However, this changes of state do not randomly occur but are governed by some physical laws. The possibility of behaviour is infinite. But with physical laws, all possible behaviours of a system can be determined [68].

Umeda et al. [68] and Keuneke [64] characterizes behaviour as one or more sequential change of physical state. Deng [60] classified behaviour representation, according to this definition, into two types: state transition (which was discussed earlier) and I/O flow of object. The I/O flow of object is the same as what is describe in functional representation. This is known as the Function-Behaviour relationship. Keuneke [64] mentioned about stimulus that activates a certain function, and this stimulus is the I/O flow of energy, material, and signal. This is also mentioned by [69]. Functions are observations of behaviours, but the functions must be intentional. Umeda et al. [68] also suggested that the selection of view in the Function-Behaviour relationship, as shown in Figure 7, is subjective so that its behaviour, its structure and the Behaviour-Structure relationship are decided automatically according to the views.

4.3. Pattern language

In any ecosystem, different species will react differently to a change or stimulus. But at the same time, some species will react in the same or similar way. This is known as nature's pattern. A phenomena happening in nature is a solution to a certain engineering problem. According to Alexander, Ishikawa, and Silverstein, pattern is a description of a problem which occurs repetitively in a certain environment, and then describes the core of the solution to that specific problem in such a way that the solution is still applicable even for infinite times, wherever the context makes it relevant. In short, pattern gives a similar solution to a similar problem in a context of interest. Pattern describes the repetition of a problem in a certain context, and then describes the core of the solution of that problem in a generic way where the solution can be applied again and again to any context which it could relate with. Therefore, the solution can be recycled provided the context is the same. Else, a different pattern might do the job better. [70]

The pattern language is a very important factor of innovation because it gives whoever that uses it the power to create an infinite variety of new and unique inventions, like a person speaking infinite variety of sentences with a language that he speaks. It sets the imagination of the designer free, while at the same time, grounded on the experience and knowledge of the user. If the designer is not knowledgeable enough on a certain topic, patterns can be used as a collection, or compilation, of reports and experiences from previous designers, which the designer can refer. This collection is of a broad and diverse range of knowledge. From this, it is evident that pattern language facilitates the idea generations and helps the designer to have reach the "lightbulb moment" in a shorter time. These patterns not only able to provide a solution to a specific field, but it can also be a spark of idea for an entirely different solution for a different problem, because each patterns helps to sustain other patterns. With the help of pattern language, problems that re-emerge and be resolved again and again with the same solution but different approaches. [70–72]

Each pattern is a generic solution to some system in the world. But in order to wield this power of creation with pattern language, the knowledge of discovering patterns which are deep is necessary. The discovered pattern must be tested against experience to see if the pattern makes the surrounding better [71]. How does a device look like, its physical geometry, doesn't really matter, but what matters the most is the function that will be performed. But these functions are dependent on the patterns of structure provided. The patterns of function is linked to the patterns of structure.

The character of nature is a specific morphological character, a geometric character, which is common to everything which are not artificial. Nature is made up of units which are almost similar instead of modular. Each and every units are unique in their own way, just like the ocean waves. But these patterns will always manifest themselves in various ways unique to the phenomena. Likewise, the elements of a device are constantly changing against time, thus, it is not the elements that are repeating within the structures, but the relationship among these elements within the structure. It can be said that a large part of the device are actually consists of patterns of relationship. These relationships are not supplementary, but essential to the elements because the elements themselves are patterns of relationships. [71]

The "pattern bridge" seems to be a promising approach, however, it is still very less explored [34]. Efforts of using pattern language to assist biomimicry in design are very few in numbers. One of the efforts done is "Patterns from Nature", which was intended to investigate and document recurring natural solutions, in a structure accessible to designers via the biomimicry portal [73]. The patterns are derived from ecosystem study. This approach is expected to facilitate the transfer of knowledge between the biology and engineering domains. However, no further publications on the progress of this project is found.

Another tool built from natural pattern is BioTRIZ. Professor Julian Vincent's research team analysed 500 biological phenomena, covering over 270 functions, at least three times at different hierarchy level. From these patterns, they had successfully cover a small part in bridging the biology-to-engineering gap by reorganizing and condensing the contradiction matrix of TRIZ according to the features which generate conflict statements and inventive principles: substance, structure, energy, information, space, and time.

Structure-Function Pattern approach [27] is a biomimetics framework based on nature's pattern, specifically the functioning structures of nature. The research team reviewed a total of 140 biological systems and from these information they identified the structure-function pattern, which are repeated protrusion, repeated tubes, asymmetry, layers, intersected layers, tube, helix, streamlined shapes, and container. However, the data of structural pattern is still insufficient and still requires more expansion for a wider range of application. Furthermore, this approach depends highly on structures while in some situation complicated processes are involved instead of structures.

5. Conclusion

This paper had given an overview of what biomimetics is, the core stages of biomimetics, the basics of how to produce a bio-inspired design, and also some research gaps. Biomimicry is not a new subject, but it lacks research activity. That is why until now there's still not much advancement, and there's no one fixed set of biomimicry steps available yet. Every available biomimicry tools are very different from one another and performs the task differently. There are still many areas of biomimicry which remains not ventured, for instance solution-based biomimetics design process. However, the trend of biomimicry methodology is somewhat clearer now than before, especially problem-driven biomimetics design process and the core stages of biomimicry, just that different authors name the stages differently.

The presented work is the foundation of a research in progress on a new biomimicry design framework based on the potential approaches presented in **Section 3**. TRIZ is a well-known and powerful set of methodology in producing inventions. But because TRIZ originated from patents of invention, the ability of TRIZ to abstract biological principles will be difficult. In order solve this issue, FBS models should be employed for the job. FBS models are widely and mainly used in computer science. But if these models are used to abstract biological systems, the finest details of the system will be able to be detected, provided there were enough biological information. Pattern language will be the "words" and "grammar" that binds all these biological "alphabets" together to be a guide for biomimicry designers. With the power of nature's pattern, bio-inspired design will no longer face any obstacle because the principle of nature will keep on flowing into the engineering world.

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