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FOR THE DEGREE OF **MASTER OF ENGINEERING**

TITLE: An Engineering Design Named Visual Functional Mapping Which Based on Functional Basis Applied on Biomimicry Field

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Last but not least, I would like to express my gratitude to my parents. Thank you for understanding and support. You are the best parents in the world. I love you forever.

ABSTRACT

As the development of the engineering field, the characteristic of the modern engineering is accepted by engineering designers. There are Globalization, efficiency and standardization. The translation problem such as language, culture and expression has been found by engineering designers. This paper introduced a new engineering design tool named visual functional mapping to solve this problem. Based on the functional basis, the paper used symbols to create eight icon, which is branch, channel, connect, control magnitude, convert, provision, signal and support, to represent all kinds of function in engineering design field. According to the research of the icons, the paper expanded the icon to make them more understanding. The biomimicry is becoming a new engineering tendency. This new engineering tools will widely use in the biomimicry and the paper also give some examples to represent how to use visual functional mapping apply in biomimicry field.

Content

List of Figures

1. Introduction

With the development of the engineering industry, society has evolved from being characterized as a mechanized industrial society, towards characterization as an information-oriented "post-industrial society." The range of engineering design has also been obviously expanded. Previously, the main engineering field was service for industrial enterprises, but now different kinds of fields, like financial, business, and tourism also need the service of engineering design. Engineering design not only exists in the industrial field, but is also widely used in other fields, including, business, tourism, entertainment, and other tertiary industry services. Meanwhile, the idea of customers becoming more and more involved in engineering design helps products and processes become adapted to the requirements of different customers. Therefore, this adaptation becomes one of the most important factors in the engineering design process.

This paper's target is focused on an easy yet important question: How do we make customers like our product? In other words, how can we perfect our product design to meet customize needs? Some researchers believe that conceptualizing, defining, or understanding an artifact or system, in terms of function, is a fundamental aspect of engineering design (Pahl and Beitz, 1984; Ullman, 1997; Ulrich and Eppinger, 1995; Hubka et al., 1988; Otto and Wood, 2001)[1][2][3][4][5]. Using a kind of representation will help a designer understand what the design's function is, so that the designer also creates a better product. Recently, much research has been conducted to find the best way to analyze or deconstruct the functions of a product. In this paper, I will introduce useful research written by Hirtz et al. (2002)[6]. They have created a standardized terminology, called Functional Basis. Hirtz's concept has given me a lot of inspiration to create and establish my own terminology.

However, why has this conceptualizing representation not been widely applied to engineering design? Perhaps because the methodology has shortcomings that need to be solved. Society changes every day. The engineering designer lives at a quick pace, but even they do not have enough time to think about conceptualizing representation in the design process. In order to follow the steps of technology development, product designers often merely change a little on a product that is already in use. Therefore, innovation is becoming more and more difficult and less common.

How to expand the designers' mind? The answer comes from nature. In recent years, a subject named biomimicry has been a great development. Biomimicry is the imitation of the models, systems, and elements of nature for the purpose of solving complex human problems [7]. More and more scientists and engineering designers use nature to solve engineering problems, such as self-healing abilities, environmental exposure tolerance and hydrophobicity. The catalog of nature's principles fills a huge database which includes useful inspirations for new designs. Designers invented radar, inspired from the bat, they invented the submarine from the fish, and invented the aircraft from the bird. With the principle of biomimicry, the principles of biology will be better used in human life.

When the example of biomimicry transfers from abstract to concrete representation, we usually use words or language to create a representation. The problem is that when authors and readers have different nationalities and different native language, the understanding of the word will be misunderstood. Figure 1 shows words which have the same meanings in different languages.

English	Chinese	French	Japanese
Branch	分支	Branche	ブランチ
Channel	引导	Canal	チャンネル
Connect	连接	Relier	つなぐ
Magnitude	量级	Ampleur	マグニチュード
Convert	转变	Convertir	変換します
Provision	供给	Disposition	提供
Signal	发信号	Signal	シグナル
Support	支持	soutien	サポート

Figure 1: Function words written in various alphabets

Although English is the most widely-used language in the world, misunderstandings are still too common to avoid. Companies such as Wal-mart, GM, or Apple, set up sub-companies in many countries and employ the local people. With globalization, the possibility of people with different nationalities, different languages, and cultures working together increases.

In order to remove misunderstanding among different people speaking different languages, using the same words expressed in four different languages, this paper provides a simpler way - symbols. Symbols have a long history. Thousands of years ago, many ancient peoples, such as the Egyptians, the Chinese and the Babylonians communicated by means of symbols. Symbols can effectively eliminate the misunderstanding in words. They are used in many fields, such as mathematics, physics, and chemistry. Whenever the nationality of scientists in an academic conference is US or China, they all use "+" to represent plus and "-" to represent minus. Obviously, no one will misunderstand the symbols in math formula. In the same way, all the physicists understand that "F" means force, and chemists know that the symbol of water is "H_2O." Symbols are not only used in academia, but also are widely used in our daily life. For instance, the traffic sign is a simple example. Red means "stop," and green means "go." These are the most basic applications.

The remainder of this paper will show a new kind of pictogram, named

Visual Functional Mapping (VFM), and the paper also will introduce how to apply it in the biomimicry field. Compared with the text-only method, visual functional mapping has many advantages. It can be prove that the engineering designer will understand prompts more legibly by using this tool.

2. Visual Functional Mapping

Frank Lloyd Wright, perhaps the greatest American architect of all time, has a famous phrase, which is "Form follows function; form and function are one."[8] This tells us that every product has two basic definitions, which are form and function. Form is the shape, visual appearance, constitution or configuration of an object. Form means what the product is, while function means what the product does. Unfortunately, this is quite often confounded by engineers. However, form and function are linked closely. Both of them are dependent on each other.

Faced with a specific product, like a cup or table, engineers should differentiate between the form and function. Both of these terms can describe the product from different approaches. For example, the form of the coffee cup (Figure 2) is a ceramic cylinder with an attached loop, glazed surfaces, flat bottom, and rounded edges. With these words, this product also could function as: a sugar scoop, a paint container, a pencil holder, a paper weight, a mixing cup, a measuring device, a door stop, or a projectile weapon. On the other hand, the function of the coffee cup is to retain liquid, insulate heat, facilitate transport, resist stains, and enable drinking. There are also many products that meet this function, such as a metal bucket or tobacco pipe (Figure 3).

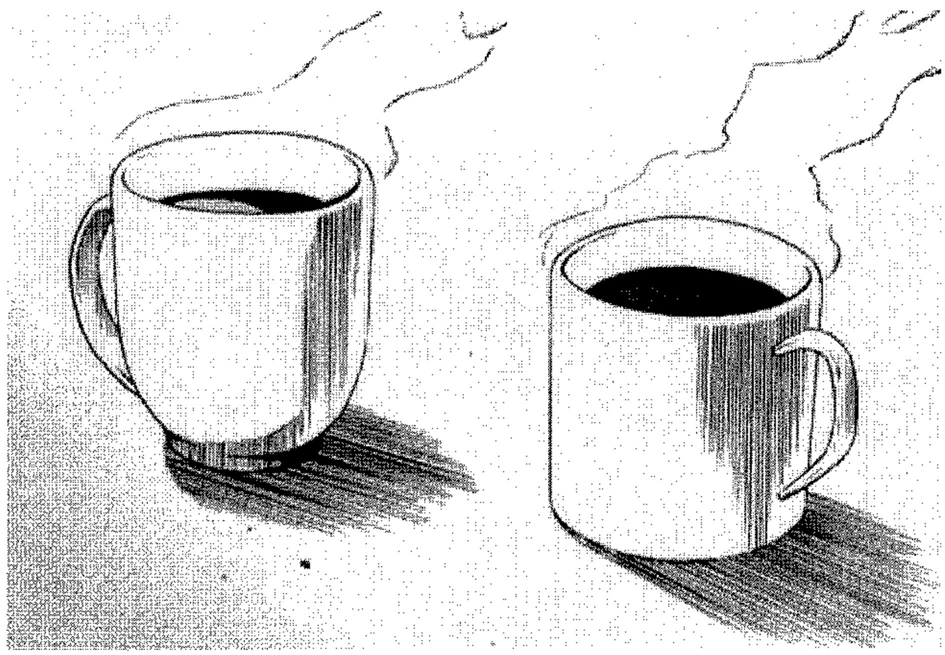


Figure 2: The coffee cup

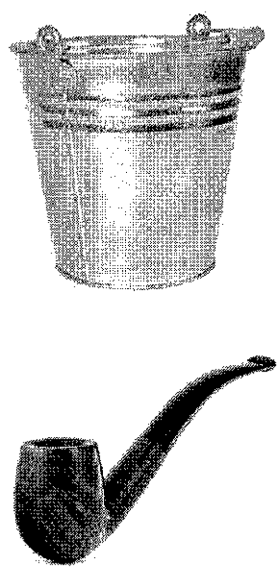


Figure 3: The metal bucket and tobacco pipe

From the example, we can know that words are not enough to describe the function of the product. We could not use function to define a product independently, because we also need to define the form of the product. Therefore, this paper changes the definition of "function." We define the function as the logical transformation of a quantity (or set of quantities) from some initial condition (or state) to another condition (or state). We also used flow charts to describe form and function.

Every engineering design product has single or multiple functions. Usually, the engineer can use several steps to describe these functions. Each step is connected to another, and the previous step will lead to the next step. Therefore, I call this process flow in this paper. Every flow will have three parts, which are input, output, and a functional icon. Figure 4 shows the single flow. Each flow stands for a function. We can create a chain composed of several visual functional mappings to describe a whole product's function.

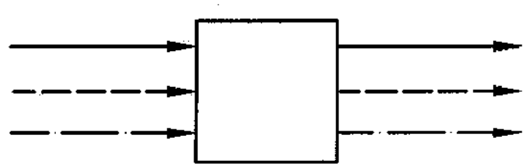


Figure 4: Visual functional mapping

The input and output are used to connect two visual functional mappings. Logically, the input is what causes the function, and the output is what is caused by the function. In the engineering design field, there are three kinds of input and output in the flow of product design. They are material, energy, and signal. The full lines are used to represent material. The dash lines are used to represent energy. The dot-dash lines are used to represent signal. Using different lines, the engineering designer will more clearly distinguish among the different functions. Figure 5 shows the three lines, represented by material, energy and signal.

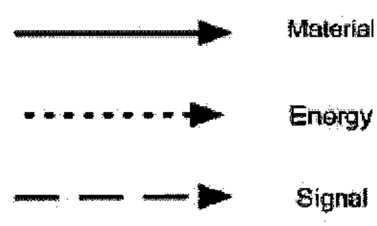


Figure 5: Input and output

People understand the principle of the submarine from fish floating and sinking. Using visual functional mapping, the function of fish will become more understandable for engineering designer to represent in engineering field. I use the easiest words to describe the function of floating and sinking in Figure 6. The fish will control the bladder muscles to decide to float or sink. If the fish wants to float, its brain will give its muscles a "relax" signal. The muscles relax, and air enters the bladder. When the bladder enlarges, the float force will be greater than the gravity of the fish. So the fish floats up. On the contrary, if fish wants to sink, the bladder muscles will tighten, and the bladder shrink. The gravity becomes greater than the float force, so that fish sinks. I made a whole function by using visual functional mappings in Figure 7. The first chain is the function of the float, and the second one is the function of the sink. Compared with the Figure 6 and 7, we can find the advantages of visual functional mapping: more logical, more understandable and more standardized. Throughout this flow chart, the engineering designer will apply the principle of fish to a submarine because the function of submarine is same as the fish.

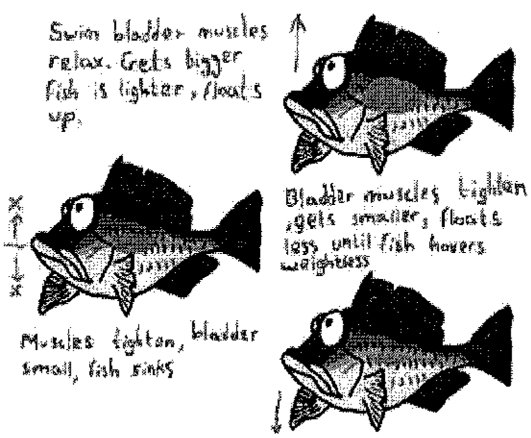


Figure 6: Function of floating and sinking

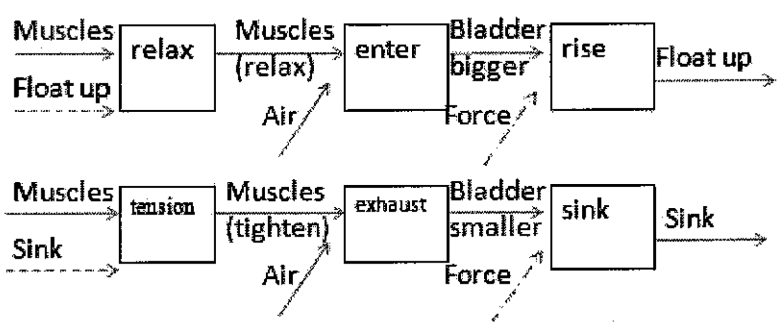


Figure 7: Functional mapping of the fish

Although the advantages of visual functional mappings are quite obvious for the field in engineering design, the disadvantages still exist. Because of using words in the flow chart, it is very free-form and open to interpretation. For instance,terms like “relax,” “enter,” and “rise” might be difficult for engineering designers to understand to visualize. Therefore, this paper provides a new method to solve this problem.

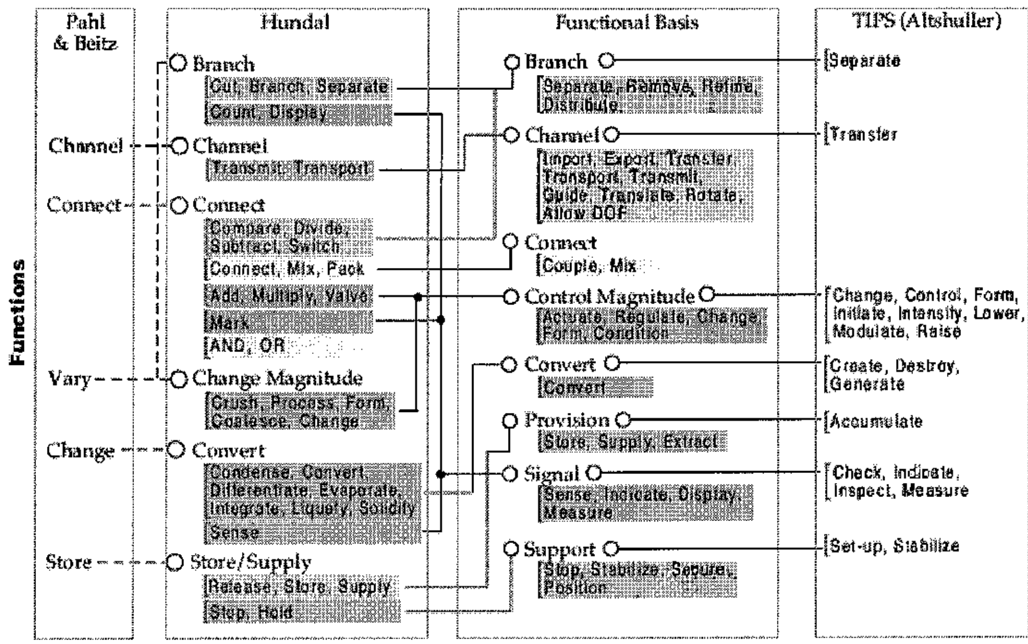


Figure 8: The development of the functional basis

The center of visual functional mapping is the functional icon (e.g. “relax” “enter” “rise”). It is the most important part in visual functional mapping because it determines how to finish the function from the input to output. We can establish a series of whole function words to cover all function. The paper on the functional basis, written by Hirtz et al. (2002), is useful for my paper. Hirtz provided a kind of new terminology to representation the function. Figure 8 shows the development of the functional basis.

3. The Background of Functional Basis

The topic of this paper is "A Functional Basis for Engineering Design: Reconciling and Evolving Previous Efforts"[6]. The paper was written by Julie Hirtz, Robert B. Stone, Daniel A. McAdams, Simon Szykman, and Kristin L. Wood. The purpose of their paper is to seek a kind of formal functional representation as a functional basis which can reconcile and integrate two independent pieces of research. They are the National Institute of Standards and Technology (NIST) research effort[9] and the functional basis effort[10]. The authors created this versatile and comprehensive design vocabulary which will enhance the range of research in engineering design, product architecture, design synthesis, and general product modeling.

The objective of engineering design is to create a product, artifact, system, or a kind of process which fulfills customer requirements for using a function. The basic concept of engineering design is conceptualizing, defining, or understanding a product, artifact, or system, in terms of function. In this paper, Hirtz et al. analyzed the difference and similarities between two efforts to create a functional basis. At the same time, they present the motivation, background, approach, results, and conclusions of their research.

Hirtz et al's creation of functional basis are triggered by many factors. Firstly, the authors created repositories for the NIST Design Repository Project[11]. However, since they faced four research problems in this project, the authors should have built a technical foundation to solve these problems. Secondly, the authors work for Ford Company at the same time designing to ensure that their product has good quality and reliability[12]. Functional basis helped engineers design a fundamental tool. The third factor was the importance of reducing ambiguity in engineering design. More accurate engineering language can avoid problems of ambiguity. Last but not least, Functional basis would increase communication with the function developer and would simplify the task of indexing and retrieving of information.

The inspiration for functional basis was Value Engineering[13] in the 1940s. Value Engineering means using some element functions to describe the whole product to cut manufacturing costs. It can describe a product's function for different product domains, though it has no single comprehensive list. Other researchers have realized the problem of engineering communication. They recognized that it is important to design a common vocabulary for engineering. During the past 40 years, many scientists create different kinds of functions based on the different ways of thinking and logic. For example, Collins et al. developed the descriptions of mechanical function in 1976[14]. They made a list of 105 unique descriptions. Koch et al. use 20 subsystem representations from living systems theory to represent mechanical design function.[15]

Recently, the author Hirtz et al. of the paper "A Functional Basis for

Engineering Design: Reconciling and Evolving Previous Efforts" have worked to develop a functional vocabulary with independent research efforts. The first is the NIST Research Effort, and the other is the Functional Basis Effort.

When Hirtz et al. worked on the NIST Research Effort, they developed a representation for product knowledge. The NIST research focused on the concepts of the function and flow. They should generate taxonomies likes atomic to allow modeling[16]. Hirtz's final aim in engineering was to achieve Hirtz's interoperability between design systems. The organization of the flow taxonomy followed a traditional approach, whereby flows are divided into material, energy and signal flows. Taxonomies are not unique. The importance was placed on the content of the taxonomy, not the specific method to organize every term.

Hirtz's functional basis research focused on researchers' needs and how to create a function representation. A kind of function and flow sets named functional basis[6]. Many other researchers developed the functional basis in many domains[17].

In this paper, the authors reconciled two results of the NIST Taxonomy and the Functional Basis because they found a high degree of similarity in the two functional vocabularies. Both of them attempt to derive a standard list of functions to describe in mechanical design field. At first, Hirtz et al. introduce a general approach to reconcile these efforts. The purpose of the functional basis is that its terms can provide coverage of all concepts. Not only can it classify the flow into material or signal or energy, it can also group any solid material into object, particulate, composite or aggregate. In general, if a new term needs be added, it must be necessary to do so in order to provide coverage to some area that is not currently fully covered. When developing the functional basis at varying levels, differences are seen in the design of new products, customer needs, and functional requirements. In general, designers want to provide sufficient information to make a design specification, analysis, or decision. At the same time, the authors also introduced a specific approach to reconciling the two functional vocabularies if the general approach cannot work. It has three steps. They are the following: named a "review" step, a "union and intersection" step, and a "reconciliation" step.

As a result, Figure 9 represents the final list. The category is mixed between the NIST taxonomies and the functional basis. In the list, there are eight fundamental categories-branch, channel, connect, control magnitude, convert, provision, signal, and support. They all are clearly defined. Then, the authors used two different methods to employ the reconciled functional basis for functional modeling. This proves that this kind of functional basis will be a useful tool for engineering design. In fact, the NIST Design Repository Project and a new program at Ford Motor Company are underway to support the authors' research on the functional basis.

Class (Primary)	*Secondary*	*Tertiary*	*Correspondents*
Branch	Separate		Isolate, sever, disjoin
		Divide	Detach, *isolate*, release, sort, split, disconnect, subtract
		Extract	Refine, filter, purify, percolate, strain, *clear*
		Remove	Cut, drill, lathe, polish, sand
	Distribute		Diffuse, dispel, disperse, dissipate, diverge, scatter
Channel	Import		Form entrance, *allow*, input, *capture*
	Export		Dispose, eject, *emit*, empty, *remove*, destroy, eliminate
	Transfer		Carry, deliver
		Transport	Advance, lift, move
		Transmit	Conduct, convey
	Guide		Direct, shift, steer, straighten, switch
		Translate	Move, relocate
		Rotate	Spin, turn
		Allow DOF	*Constrain*, unfasten, unlock
Connect	Couple		Associate, connect
		Join	Assemble, fasten
		Link	Attach
	Mix		Add, blend, coalesce, combine, pack
Control Magnitude	Actuate		Enable, initiate, start, turn-on
	Regulate		Control, equalize, limit, maintain
		Increase	*Allow*, open
		Decrease	Close, delay, interrupt
	Change		Adjust, modulate, *clear*, demodulate, invert, normalize, rectify, reset, scale, vary, modify
		Increment	Amplify, enhance, magnify, multiply
		Decrement	Attenuate, dampen, reduce
		Shape	Compact, compress, crush, pierce, deform, form
		Condition	Prepare, adapt, treat
	Stop		End, halt, pause, interrupt, restrain
		Prevent	Disable, turn-off
		Inhibit	Shield, insulate, protect, resist
Convert	Convert		Condense, create, decode, differentiate, digitize, encode, evaporate, generate, integrate, liquefy, *process*, solidify, transform
Provision	Store		Accumulate
		Contain	*Capture*, enclose
		Collect	Absorb, consume, fill, reserve
	Supply		Provide, replenish, retrieve
Signal	Sense		Feel, determine
		Detect	Discern, perceive, recognize
		Measure	Identify, *locate*
	Indicate		Announce, show, denote, record, register
		Track	Mark, time
		Display	*Emit*, expose, select
	Process		Compare, calculate, check
Support	Stabilize		Steady
	Secure		*Constrain*, hold, place, fix
	Position		Align, *locate*, orient
		Overall increasing degree of specification →	

Figure 9: List of functional basis

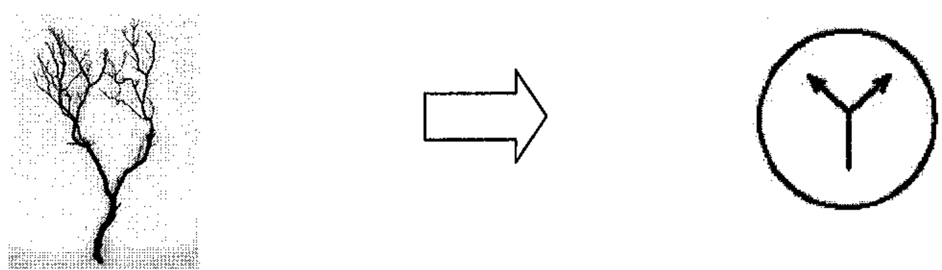
At the end of the paper, the authors make compassion with the new functional basis with both of the earlier efforts. The new functional basis advances these other efforts, since it provides a better method for understanding and representing the product in engineering.

4. Icon Design

As previously stated in this paper, symbols are a better method to remove misunderstanding. Although the functional basis only has eight series of words to describe all functions, there still is misunderstanding in representing the functions. Therefore, I have designed the symbols to take the place of the functional basis. The following sections describe the new icons.

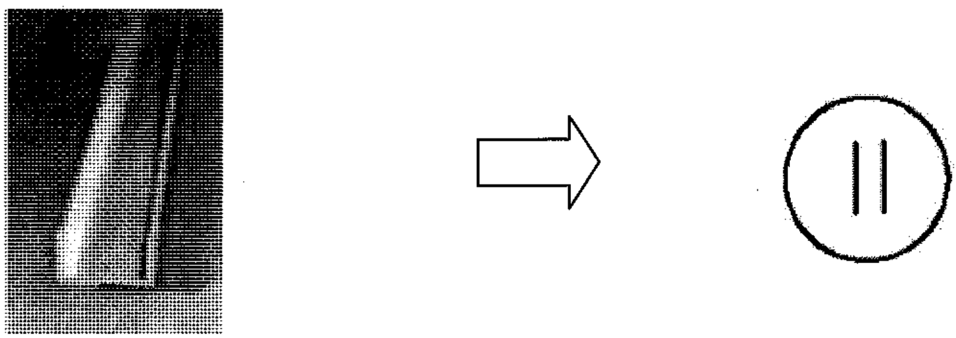
4. 1 Branch

When thinking of "branch," imagine a tree branch at first. Based on the image of the tree branch, I designed the functional icon branch. As the function, the branch means to cause a flow (material, energy, and signal) in order to no longer be joined or mixed.



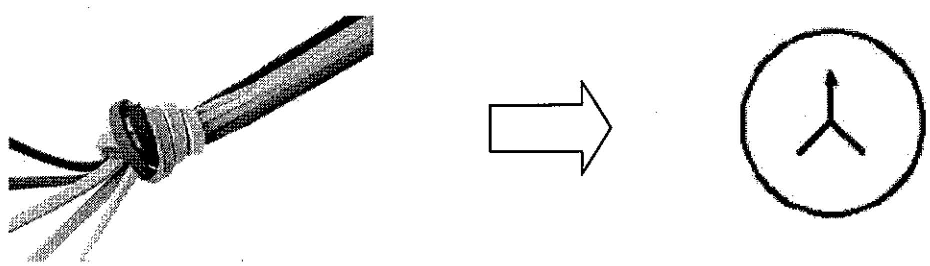
4. 2 Channel

Channel used to be a noun, meaning a passage for water to flow through. As a verb, channel means direct the flow of. Therefore, I designed the functional icon of channel based on the image of the groove. As the function, the channel means to cause a flow (material, energy, and signal) to move from one location to another location.



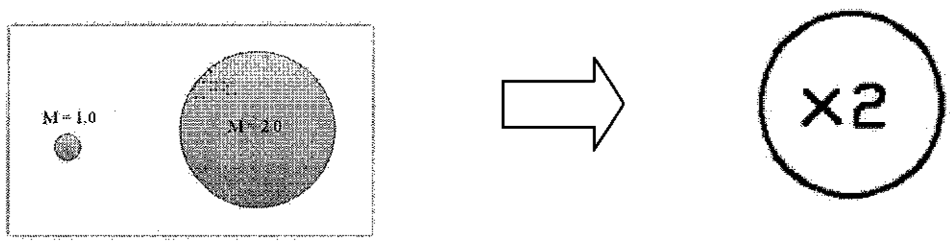
4. 3 *Connect*

Connect means to put together two or more pieces. For example, two cities are connected by a railway. I designed the functional icon of connect as the flowed image. As the function, the connect means to bring two or more flows (material, energy, and signal) together.



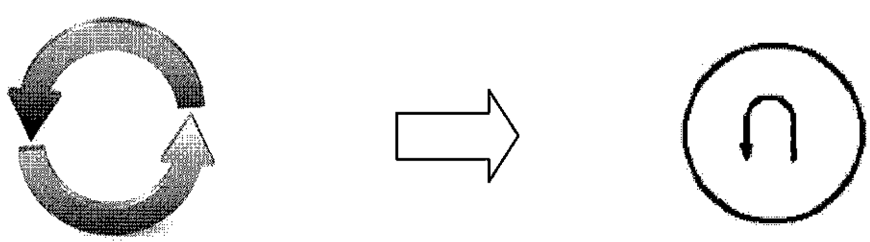
4. 4 *Control Magnitude*

Control magnitude means to alter or govern the size or amplitude of a flow (material, energy, and signal). Altering the control magnitude will change the property of the flow. I designed the functional icon for control magnitude using a multiple sign because the most common magnitude to be controlled is scale.



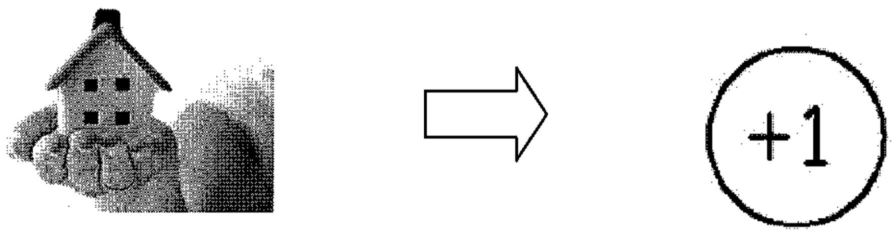
*4. 5 **Convert***

Convert means to change from one system to another one or to a new plan. Convert is a basic verb in English, so that it has many explanations. I designed the functional icon based on its basic explanation. As the function, the convert means to change from one from of a flow (material, energy, and signal) to another.



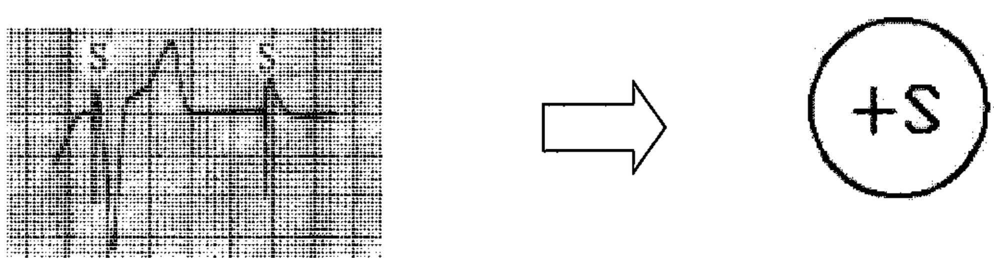
*4. 6 **Provision***

Provision means the activity of supplying or providing something. In my opinion, it means something comes from zero to one. Therefore, I designed the functional icon, which uses plus one. As the function, the provision means to accumulate or provide material or energy flow.



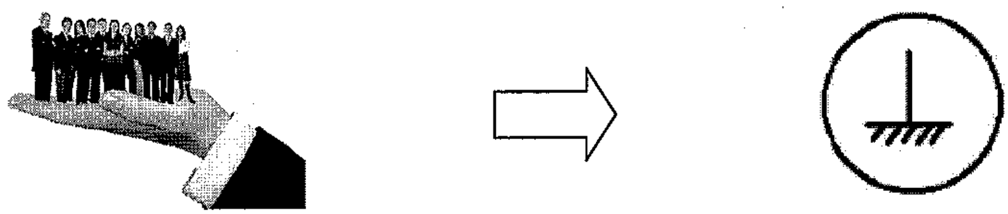
*4. 7 **Signal***

When signal is a noun, it means any communication that encodes a message. When signal is a verb, it means communicate by signals. Therefore, I designed the functional icon of signal similar to the functional icon of provision. As the function, the signal means to provide information on a material, energy or signal flow as an output signal flow.



4. 8 ***Support***

Support means an activity of providing or maintaining by supplying with necessities. For a instance, a stick needs something to help it to stand on the ground. According to this instance, I designed the functional icon of support. As the function, the support means to firmly fix a material into a defined location, or secure an energy or signal into a specific course.



5. Research of The Icons

As the designer of the functional icons, I want to know whether they are easily understood by the engineering designer. Therefore, I decided to take a survey in order to get the feedback from others. The feedback will let me prove the viability of the functional icon. In the survey, the participants matched the eight pairs of functional icons. I tracked the number of mismatched pairs. There were 19 participants in the survey, including 10 male and 9 female. Sixteen of them were students; the others were instructors. According to major which they study in, 10 persons' major was engineering; the others are business, nursing and dental. Finally, fourteen of them were natural United States citizens, 5 were of international origin.

Analysis of functional icons

According to the gender, the major and the nationality, I made charts to analyze the data respectively.

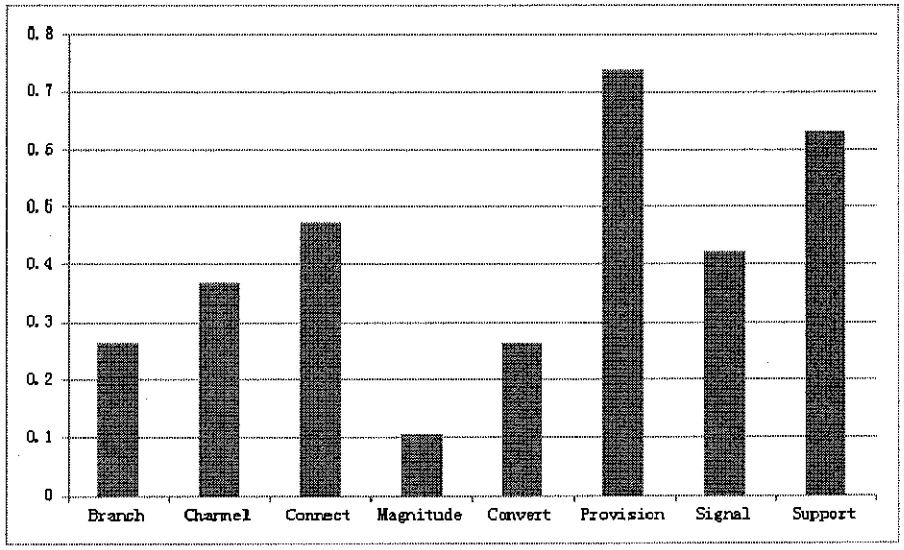


Chart 1: The probability of error in the total samples

Chart 1 shows the probability of error in the total samples. We can find the functional icons of provision and support have the highest possibility of being misidentified.

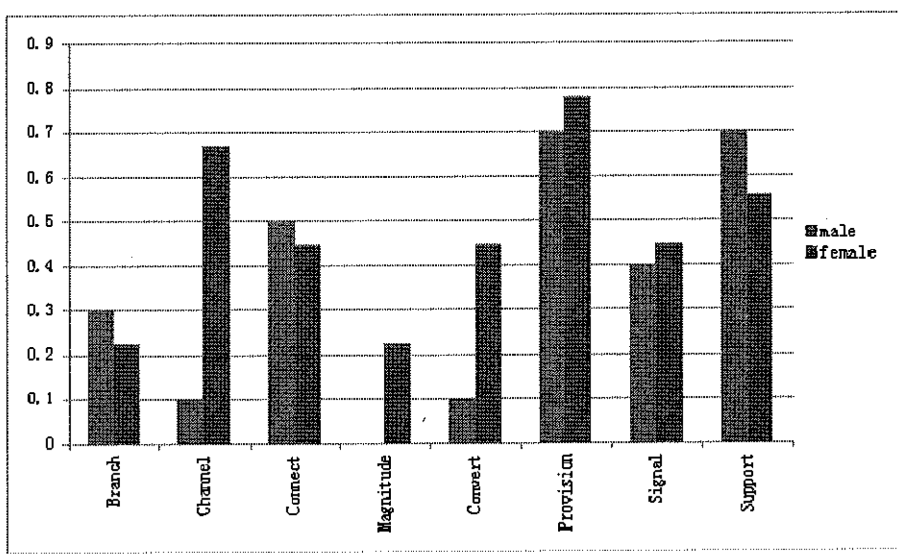


Chart 2: The probability of error compare with male and female

Chart 2 shows the probability of error which compares with male and female. Obviously, the possibility of channel, control magnitude and convert being misidentified were highest by female participants.

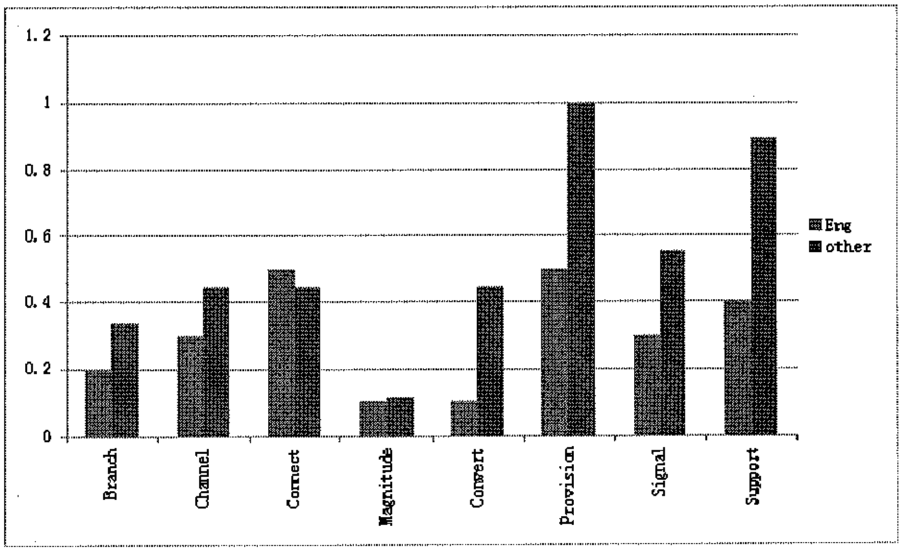


Chart 3: The probability of error compare with engineering and other

Chart 3 shows the probability of error which compares with engineering and other majors. This chart is the most important data in my data analysis because the functional icons will be applied in engineering field. If the person who studies in engineering makes a high possibility of error, it seems that the functional icon would need to be redesigned to be more easily recognized by engineering designers. Throughout the histograms, we find the possibility of misidentification by non-engineering majors is higher than by engineering majors. The engineering majors were more successful understanding the functional icons.

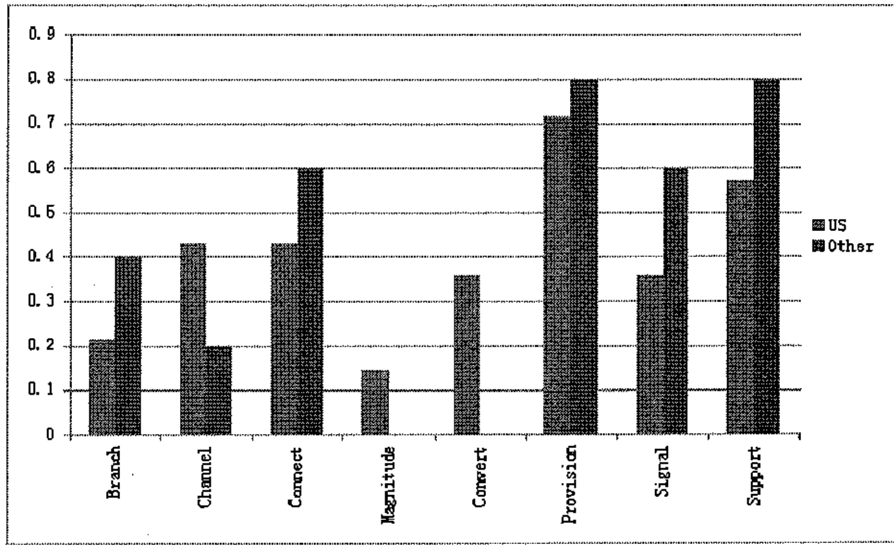


Chart 4: The probability of error compare with US and other

Chart 4 shows the probability of error which compares with US and other nationalities. From the histograms, the possibility of error has no obvious distinction on both columns.

If the survey's sample was dramatically increased in future studies, it would more accurately represent the population. However, due to resource limitations, I was unable conduct additional surveys. Despite the limited sample size, we still can identify some problems with the functional icons. First of all, the eight icons are still not universally identifiable by everyone. Many people cannot distinguish the function of these icons, because they think the icon are too abstract and difficult to understand. Secondly, some people have very different understanding of these functions, and they often suggested alternatives of their own design to replace mine. Finally, they still disagree with my design after I explain my idea of the functional icons.

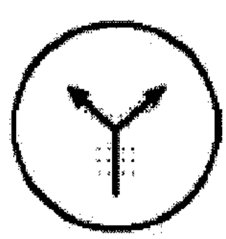
To improve the granularity of the functional icons, there is a method to expand the detail of the images. According to the list of functional basis, the functions have the secondary categories, as expansions of their primary categories. For example, there are two categories under the branch categories, named distribute and separate. They also have a further explanation to make the function more specific and accurate.

6. Secondary Icons

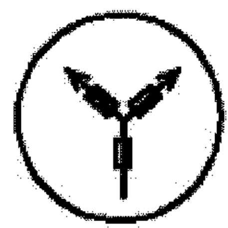
I designed secondary icons to make the functional icons more specific and accurate. There are closely linked by the secondary functional basis and the primary functional basis. Therefore, I designed the secondary icons to provide additional detail to the primary icons. The uniformity between primary and secondary icons will help people understand the link of the primary icons and the secondary icons.

6.1 Branch

There are two functional icons associated with "branch". **Distribute** means to cause a flow (material, energy, and signal) to break up. The individual bits are similar to each other and the undistributed flow. For example, an atomizer distributes hair-styling liquids to hold hair in the desired style. **Separate** means to isolate a flow (material, energy, and signal) into distinct components. The separated components are distinct from the flow before separation, as well as each other. For example, a glass prism separates light into different wavelength components to produce a rainbow.



Distribute

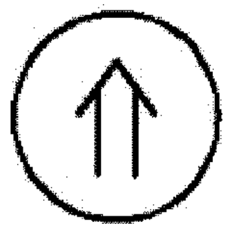


Separate

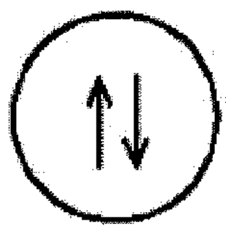
6.2 Channel

There are four functional icons under "channel". **Import** means to bring in a flow (material, energy, and signal) from outside the system boundary. For example, a physical opening at the top of a blender pitcher imports a solid into the system. **Export** means to send a flow (material, energy, and signal) outside the system boundary. For example, pouring blended food out of a standard blender pitcher export liquid from the system. **Transfer** means to shift, or convey, a flow (material, energy, and signal) from one place to another. For example, a coffee maker transfers liquid from its reservoir through its heating chamber and then to the filter basket. **Guide** means to direct the course of a flow (material, energy, and signal) along a specific path. For example, a domestic HVAC system guides gas around the house to the correct locations via a set of ducts.

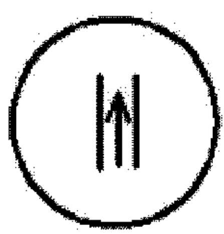
Import



Export



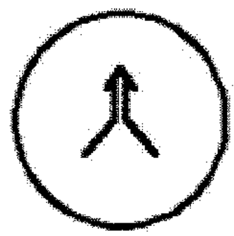
Transfer



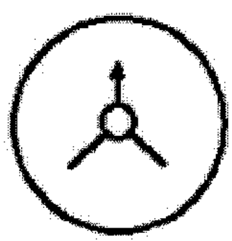
Guide

6.3 Connect

There are two functional icons under “connect”. **Couple** means to join or bring together flows (material, energy, and signal) such that the members are still distinguishable from each other. For example, a standard pencil couples an eraser and a writing shaft. **Mix** means to combine two flows (material, energy, and signal) into a single, uniform homogeneous mass. For example, a shaker mixes a paint base and its dyes to form a homogenous liquid.



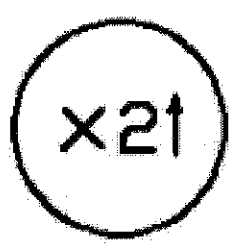
Couple



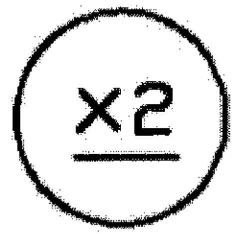
Mix

6.4 Control Magnitude

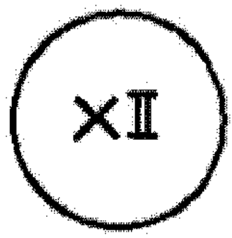
There are four functional icons under "Control Magnitude". **Actuate** means to commence the flow of energy, signal, or material in response to an imported control signal. For example, a circuit switch actuates the flow of electrical energy and turns on a light bulb. **Regulate** means to adjust the flow of energy, signal, or material in response to a control signal, such as a characteristic of a flow. For example, turning the values regulate the flow rate of the liquid flowing from a faucet. **Change** means to adjust the flow of energy, signal, or material in a predetermined and fixed manner. For example, in a hand held drill, a variable resistor changes the electrical energy flow to the motor thus changing the speed the drill turns. **Stop** means to cease, or prevent, the transfer of a flow (material, energy, and signal). For example, a reflective coating on a window stops the transmission of UV radiation through a window.



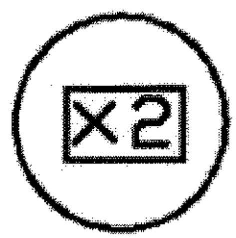
Actuate



Regulate



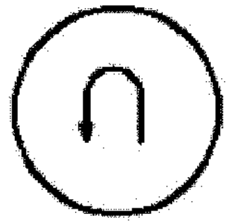
Change



Stop

6.5 Convert

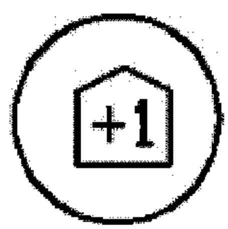
There are no secondary icons under "convert", because the function of convert is accurate enough to describe the product. For example, an electrical motor converts electricity to rotational energy.



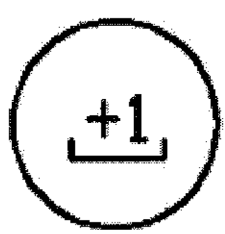
Convert

6.6 Provision

There are two functional icons under "provision". **Store** means to accumulate a flow. For example, a DC electrical battery stores the energy. **Supply** means to provide a flow from storage. For example, in a flashlight, the battery supplies energy to the bulb.



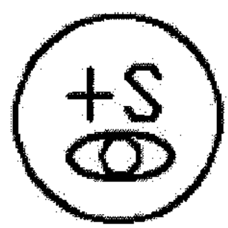
Store



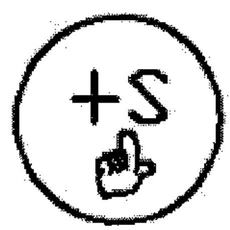
Supply

6.7 Signal

There are two functional icons under "signal". **Sense** means to perceive, or become aware, of a flow. For example, an audiocassette machine senses if the end of tape has been reached. **Indicate** means to make something know to the user about a flow. For example, a small window in the water container of a coffee maker indicates the level of water in the machine.



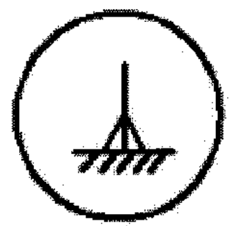
Sense



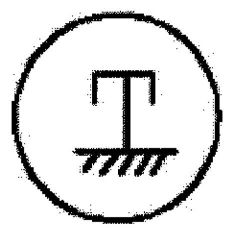
Indicate

6.8. Support

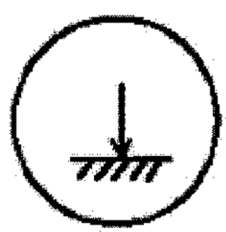
There are three functional icons under "support". **Stabilize** means to prevent a flow from changing course or location. For example, on a typical canister vacuum, the center of gravity is placed at a low elevation to stabilize the vacuum when it is pulled by the hose. **Secure** means to firmly fix a flow path. **Position** means to place a flow (material, energy, and signal) into a specific location or orientation. For example, the coin slot on a soda machine positions the coin.



Stabilize



Secure



Position

There are 20 secondary functional icons included in "convert" in this paper. They all have their own definition and a basic example to understand. When the functional icons combine with the visual functional mapping, the engineering product can be represented by them to satisfy with the customers' need.

7. Usage of The Functional Mapping on Biomimicry Field

With the development of engineering design, biomimicry is playing an important role in the field [18]. Biomimicry (from bios, meaning life, and mimesis, meaning to imitate) is a new discipline that studies nature's best ideas and then imitates these designs and processes to solve human problems. There are many examples of using biomimicry. Studying a leaf to invent a better solar cell is an example. I think of it as "innovation inspired by nature." The core idea is that nature, by necessity, has already solved many of the problems we are grappling with. Animals, plants, and microbes are the consummate engineers. They have found what works, what is appropriate, and most important, what lasts here on Earth. This is the real news of biomimicry: After 3.8 billion years of research and development, failures are fossils, and what surrounds us is the secret to survival. Because of the great value of biomimicry, more and more engineering designers want to use the theory of biomimicry in their work.[19]

In order to represent specific things in nature, engineering designers need a kind of engineering language to help them understand the function of nature and communicate with other who has different native language. The visual functional mapping will be a useful conceptualizing representation to link the nature and engineering field.

The illustration of visual functional mapping will use three examples of the product which use the biomimicry principle. In Figure 10, we can see the principle of fish's float and sink. As we all know, the invention of submarine is a good example of natural inspiration. In Figure 11, the principle of submarine's function is similar with the principle of fish.

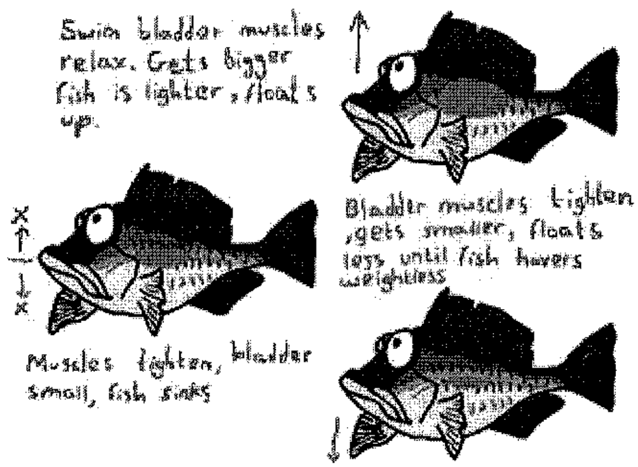


Figure 10: Principle of fish's floating and sink

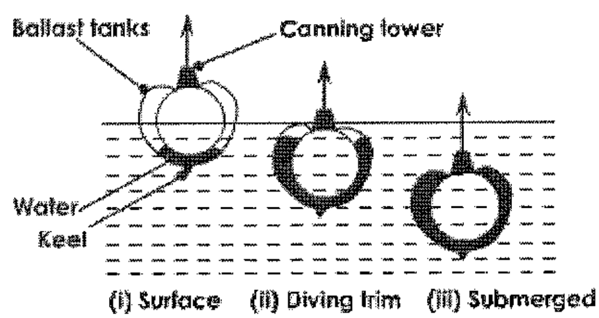


Figure 11: Principle of submarine's function

Now we can establish the chain chart of the fish and submarine by using the visual functional mapping. Shown below in Figure 12 and 13 are the chain charts of the function flows. It is only three symbols which are simple, visualize and universal in the chain chart by using visual functional mapping, however they can fully describe all the functions reasonably. Compare with two chain charts, we can find that the functional icons from the chain charts are the same. Therefore we can consider that the fish and the submarine have a lot of contact on the function. If we want to design a product like a submarine, we can be inspired from the fish.

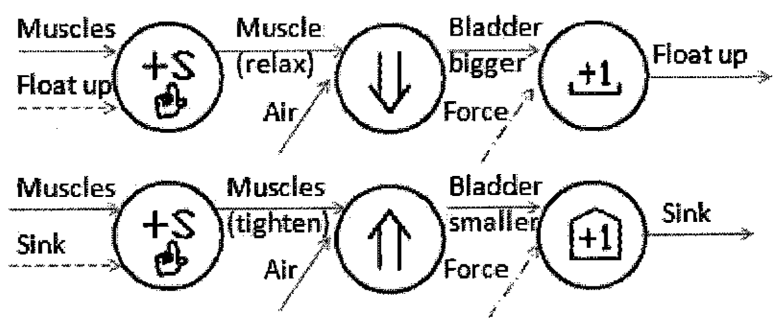


Figure 12: Visual functional mapping of fish

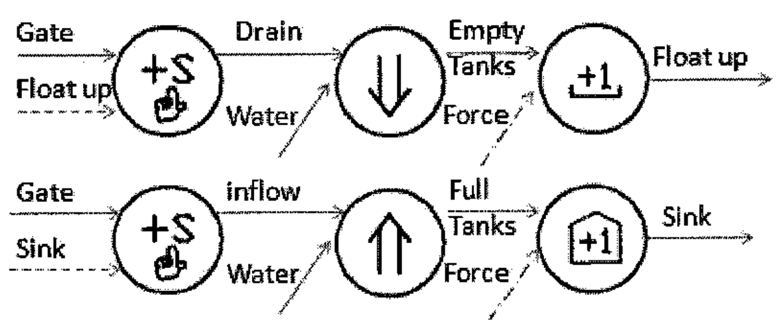


Figure 13: Visual functional mapping of submarine

From the example of the fish and submarine, we can clearly find that using visual functional mapping will make the design process easier. The engineering designer can use visual functional mapping to define everything in the nature, and then build a database to share with each other. Once the database is established, the engineering designer only need to match the functional icon with the product he wants to design.

There are two examples to introduce how to establish the visual functional mapping from the nature thing and apply to improve the product which already existing.

Solar energy is one potential method to solve the energy crisis. Therefore, more and more solar panels are set up to absorb solar energy. However, how to make the solar panels more efficient is an important problem for the engineer. From the biomimicry database, we can find a solution. Leaves of the plant maximize exposure to sun to maximize photosynthesis by moving throughout the day. Figure 14 shows its visual functional mapping. According the mapping of the leaves, we find the key function of the solar panels is "convert" and "change". The engineering designer knows how to improve the solar panels to make it more efficient. As the Figure 15, the solar panels can change the direction to facing the sun all the time.

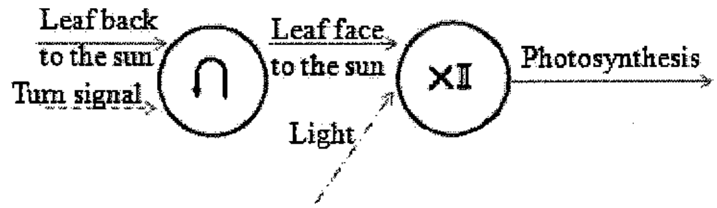


Figure 14: Visual functional mapping of leaves

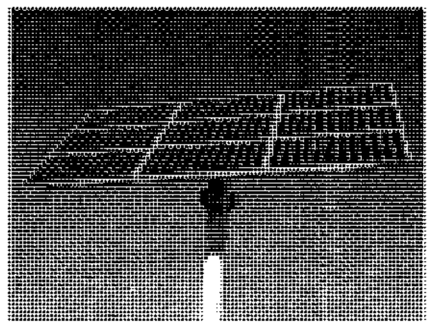


Figure 15: The solar panel

The development of heat-retaining fabric is another example. People want to wear high-tech clothing that can meet the requirements. The animal kingdom already had to solve this problem. Hair of the polar bear insulates it from cold because it has low emissivity in infrared. The Figure 16 shows the visual functional mapping of this function. According the visual functional mapping, the engineer can improve fabrics to make warmer. (Figure 17)

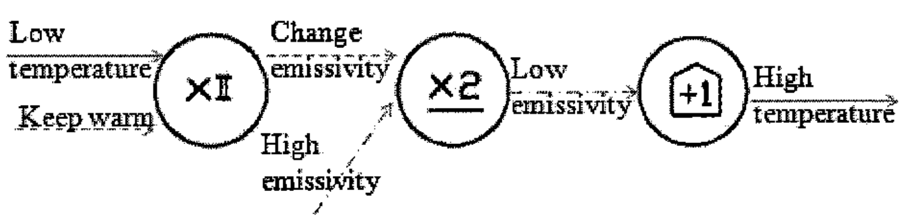


Figure 16: Visual functional mapping of hair

Figure 17: Fabric to make heat

8. Conclusions and Further Study

In engineering design field, conceptualizing representation provides a feasible method for understanding and representing an overall product function. Visual functional mapping is a useful conceptualizing representation to solve the problem which the engineering designer faces. Though analyzing the principle of biomimicry, the engineering designer can find the contract of the nature and the product. Visual functional mapping connects biomimicry and engineering.

Although the visual functional mapping is useful, it is in its infancy and still needs refinement. Firstly, from the survey, we can know that the design of the functional icons is not accepted by everyone. According to the analysis of the data, the icons which have a high possibility to mistaken interpretation should be redesigned, such as the case with "provision" and "support". If we want that these functional icons to be used around the world, we must make sure that they are universally understood by most of. Secondly, building a huge database of icon strings, including nature, will be the most important step for using the biomimicry principle for engineering. The database which can be shared with engineers around the world is so useful that all engineering designs can benefit. Finally, the logic of using icon-chains is a key premise of the paper. If the engineering designer can define the needed chain, they can search biomimicry databases for common chains found in nature.

References

1. Pahl, G. and W. Beitz (1984), *Engineering Design: A Systematic Approach*, Design Council, London.

2. Ullman, D. (1997), The Mechanical Design Process, McGraw-Hill, New York, 2nd edition.

3. Ulrich, K. T., and Eppinger, S. (1995), Product Design and Development, McGraw-Hill, NY.

4. Hubka, V., Andreasen, M., Eder, W. and Hills, P. (advisory editor) (1988), *Practical Studies in Systematic Design*, Butterworths, London.

5. Otto, K. and Wood, K. (2000), *Product Design: Techniques in Reverse Engineering and New Product Development*, Prentice Hall, Upper Saddle River, NJ.

6. Hirtz, Julie, Robert B. Stone, Daniel A. McAdams, Simon Szykman, and Kristin L. Wood. 2002. "A Functional Basis for Engineering Design: Reconciling and Evolving Previous Efforts." Research in Engineering Design 13(2):65-82

7. Janine M. Benyus, 1998. "Biomimicry; Innovations inspired by nature", Harper Perennial Press, 1998, P. 308, ISBN 978-0-06-053322-9

8. Stone, R., Wood, K., and Crawford, R. (1999a), "Product Architecture Development with Quantitative Functional Models," *Proceedings of DETC99*, DETC99/DTM-8764, Las Vegas, NV.

9. Akiyama, K. (1991), Function Analysis: Systematic Improvement of Quality Performance, Productivity Press.

10. Stone, R. and Wood, K. (2000), "Development of a Functional Basis for Design", *Journal of Mechanical Design, 122(4):359-370.*

11. Szykman, S., R. D. Sriram and S. J. Smith (Eds.) (1998), *Proceedings of the NIST Design Repository Workshop, Gaithersburg, MD, November 1996.*

12. Hundal, M. (1990), "A Systematic Method for Developing Function Structures, Solutions and Concept Variants", *Mech. Mach. Theory*, 25(3):243-256.

13. VAI (Value Analysis Incorporated) (1993), *Value Analysis, Value Engineering, and Value Management*, Clifton Park, New York.

14. Collins, J., Hagan, B., and Bratt, H. (1976), "The Failure-Experience Matrix - a Useful Design Tool," Transactions of the ASME, Series B, Journal of Engineering in Industry, 98:1074-1079.

15. Koch, P., Peplinski, J., Allen, J. and Mistree, F. (1994), "A Method for Design Using Available Assets: Identifying a Feasible System Configuration,"*Behavioral Science*, 30:229-250.

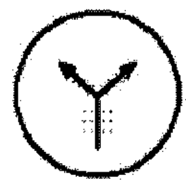
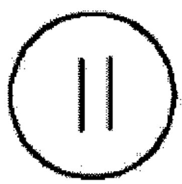
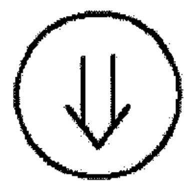
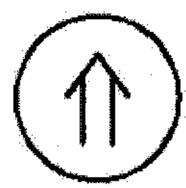
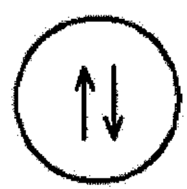
16. Little, A., Wood, K., and McAdams, D. (1997), "Functional Analysis: A Fundamental Empirical Study for Reverse Engineering, Benchmarking and Redesign," *Proceedings of the ASME Design Theory and Methodology Conference*, Sacramento, California.

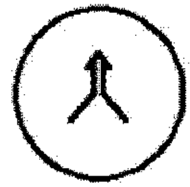
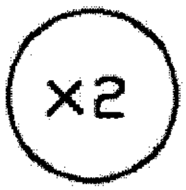
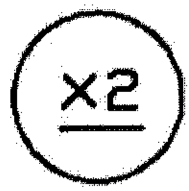
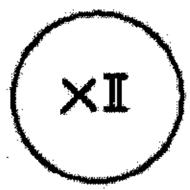
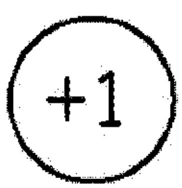
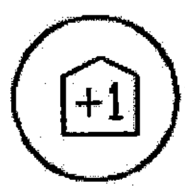
17. Stone, R. and Wood, K. (1999b), "Development of a Functional Basis for Design," Proceedings of *DETC99*, DETC99/DTM-8765, Las Vegas, NV.

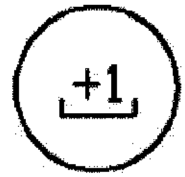
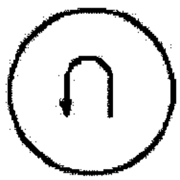
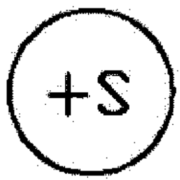
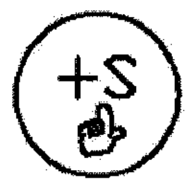
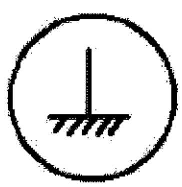
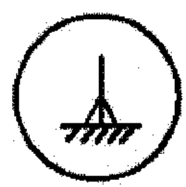
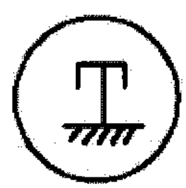
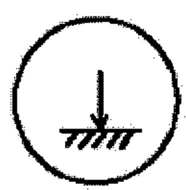
18. Yoseph Bar-Cohen, "Biomimetics: Mimicking and inspired-by biology", Proceedings of the SPIE smart structure conference, San Diego, CA, SPIE V ol. 5759-02, March 7-10,2005.

19. Hanrot Stephane, "Biomimicry: A New- Approach to Enhance the Efficiency of Natural Ventilation Systems in Hot Climate". *International Seminar Arquitectonics Network, Architecture and Research, Barcelona 1st June 2010.*

Appendix 1: list of icons

Primary Icons	Image	Secondary Icons	Image
Brach		Separate	
		Distribute	
Channel		Import	
		Export	
		Transfer	
		Guide	

Connect		Couple	
		Mix	
Magnitude		Actuate	
		Regulate	
		Change	
		Stop	
Provision		Store	

		Supply	
Convert		None	
Signal		Sense	
		Indicate	
Support		Stabilize	
		Secure	
		Position	

Appendix 2: Icons definitions and examples

1.Branch. To cause a flow (material, energy, and signal) to no longer be joined or mixed.

a) Separate. To isolate a flow (material, energy, and signal) into distinct components. The separated components are distinct from the flow before separation, as well as each other.

b) Distribute. To cause a flow (material, energy, and signal) to break up. The individual bits are similar to each other and the undistributed flow.

2.Channel. To cause a flow (material, energy, and signal) to move from one location to another location.

a) Import. To bring in a flow (material, energy, and signal) from outside the system boundary.

b) Export. To send a flow (material, energy, and signal) outside the system boundary.

c) Transfer. To shift, or convey, a flow (material, energy, and signal) from one place to another.

d) Guide. To direct the course of a flow (material, energy, and signal) along a specific path.

3.Connect. To bring two or more flows (material, energy, and signal) together.

a) Couple. To join or bring together flows (material, energy, and signal) such that the members are still distinguishable from each other.

b) Mix. To combine two flows (material, energy, and signal) into a single, uniform homogeneous mass.

4.Magnitude. To alter or govern the size or amplitude of a flow (material, energy, and signal).

a) Actuate. To commence the flow of energy, signal, or material in response to an imported control signal.

b) Regulate. To adjust the flow of energy, signal, or material in response to a control signal, such as a characteristic of a flow.

c) Change. To adjust the flow of energy, signal, or material in a predetermined and fixed manner.

d) Stop. To cease, or prevent, the transfer of a flow (material, energy, and signal).

5.Convert. To change from one from of a flow (material, energy, and signal) to another.

6.Provision. To accumulate or provide a material or energy flow.

a) Store. To accumulate a flow.

b) Supply. To provide a flow from storage.

7.Signal. To provide information one a material, energy or signal flow as an output signal flow.

a) Sense. To perceive, or become aware, of a flow.

b) Indicate. To make something know to the user about a flow

8.Support. To firmly fix a material into a defined location, or secure an energy or signal into a specific course.

a) Stabilize. To prevent a flow from changing course or location.

b) Secure. To firmly fix a flow path.

c) Position. To place a flow (material, energy, and signal) into a specific location or orientation.

Appendix 3: Survey

Survey 1

Gender: □Male □Female

Level: □Freshman □Sophomore □Junior □Senior □Graduate □Instructor

Major: ______________________

Citizenship: ______________________

Please fill the options in the blanks.

A.  (   )

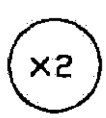
Magnitude

B.  (   )

Signal

C.  (   )

Branch

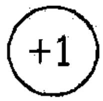
D. 

(   )

Support

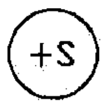
E.  ( )

Convert

F. 

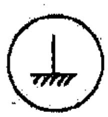
( )

Channel

G. 

( )

Connect

H.  ( )

Provision