Article

Semantic Reasoning of Product Biologically Inspired Design Based on BERT

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Abstract: Bionic reasoning is a significant process in product biologically inspired design (BID), in which designers search for creatures and products that are matched for design. Several studies have tried to assist designers in bionic reasoning, but there are still limits. Designers' bionic reasoning thinking in product BID is vague, and there is a lack of fuzzy semantic search methods at the sentence level. This study tries to assist designers' bionic semantic reasoning in product BID. First, experiments were conducted to determine the designer's bionic reasoning thinking in top-down and bottom-up processes. Bionic mapping relationships, including affective perception, form, function, material, and environment, were obtained. Second, the bidirectional encoder representations from transformers (BERT) pretraining model was used to calculate the semantic similarity of product description sentences and biological sentences so that designers could choose the high-ranked results to finish bionic reasoning. Finally, we used a product BID example to show the bionic semantic reasoning process and verify the feasibility of the method.

Keywords: biologically inspired design; bionic reasoning; semantic matching

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1. Introduction

1.1. Product Biologically Inspired Design

People get inspiration from one domain and apply it to another domain, which is called analogy [1]. Biologically inspired design (BID) takes biology as the source domain, and engineering, architecture, and industrial products can be target domains [2,3]. Product BID is a biologically inspired design in which the target domain is the product appearance.

The BID strategy can be divided into a top-down approach and a bottom-up approach. In the top-down approach [4], there is always a well-defined problem, and designers search for analogous solutions in nature to solve it. In the bottom-up approach, designers start from biology to find suitable design objects.

There are two significant processes in product BID: bionic reasoning and bionic expression (Figure 1). In bionic reasoning, designers search for creatures and products that are matched according to the design goal [5,6]. In bionic expressions, designers use the creature and product obtained by reasoning to draw detailed sketches and build 3D models accomplishing the product BID [7].

Figure 1. Product design process.

1.2. Bionic Reasoning

Bionic reasoning is important for product BID. Choosing related creatures and products can make designers' thinking and sketching in the subsequent bionic expression stage smoother, and the bionic product can convey harmonious imagery and aesthetics for users. This stage requires comprehensive knowledge of products, creatures and product design, which is difficult for designers, especially novices.

Several studies have attempted to assist designers in bionic reasoning accurately and efficiently through scientific methods, including (1) templates, (2) keyword-based search, (3) perceptual matching and (4) morphological matching.

(1) Templates are used to guide analogy thinking by asking designers to write down the corresponding information of the source domain and target domain and are proven to improve the accuracy of bionic reasoning [8,9].

(2) Biology and engineering databases are established to accomplish bionic reasoning by keyword-based search, which is a precise search, and the results are limited [10]. To improve keyword-based search, a 'bridging' method is introduced to identify nonobvious but highly relevant keywords, including nouns and verbs [11–13]. Biological or engineering keywords are expanded by adding their troponym or hypernym from the online lexical WordNet.

(3) The perceptual matching method is another semantic approach for bionic reasoning. By scoring the affective perception of creatures and products with the same index, researchers obtain creatures and products that have similar affective perceptions for subjects. Luo et al. [14] and Yuan et al. [15] used perceptual evaluation to predict users' preference for creatures in BID.

(4) For morphological reasoning, Luo et al. [16] introduced a shape context algorithm to find a biological contour that is most similar to the given product contour. Zhu [17] used topological similarity to perform bionic morphological reasoning by analyzing the topological relation of organisms and products.

However, there are also limits in the above bionic reasoning methods. First, there is a lack of in-depth research on designers' ideation in bionic reasoning. In addition, 'bridging' expanded the search result, but it is still a precise search and can only search for words, not sentences. There is a lack of fuzzy semantic search methods at the sentence level. Finally, perception matching requires a large number of users to score, which is inconvenient and inefficient.

1.3. Bidirectional Encoder Representations from Transformers (BERT) Pretraining Model

BERT is a pretraining language model proposed by Google that has a deep understanding of natural language. There are two unsupervised pretraining tasks of BERT: the masking language model (MLM) and next sentence prediction (NSP) [18]. Learning on large-scale unlabeled training data through two pretraining tasks made BERT have great

performance on various downstream nature language processing (NLP) tasks, such as machine translation, knowledge extraction, text classification and question answering systems [19–22].

Since there are few studies on designers' real reasoning thinking and sentence-level fuzzy semantic reasoning in product BID, this study conducts two experiments to determine designers' bionic reasoning thinking mode first, and then uses the natural language processing model BERT to realize bionic semantic reasoning.

2. Experiment

2.1. Study 1: Bionic Reasoning Experiment from Product to Biology

The purpose of this experiment is to explore designers' bionic reasoning modes and their frequency in bottom-up product bionic design.

2.1.1. Subjects

A total of 12 industrial design graduate students (7 male and 6 female, aged from 22 to 29), all of whom had more than four years of product design experience, were chosen as subjects to perform the bionic reasoning task.

2.1.2. Stimuli

Three experts discussed bionic products with the goal of covering as many product categories and product use environments as possible. Eight common products are selected: airplane, desk lamp, humidifier, motorcycle helmet, sofa, automobile, water cup, and speedboat, which cover complex products and simple products.

2.1.3. Procedure

Participants are invited to come up with as many organisms as possible according to each product provided in Section 2.1.2, assuming they are working on a product BID. After their reasoning, participants are asked to write down in brief sentences the reason for each product-to-biology combination.

The specific product appearance is not displayed to avoid interfering with the subjects' ideation. Meanwhile, subjects are given the authority to search for information from the internet.

2.1.4. Results

Statistics of the reasoning showed that on average, each subject inferred 3.09 corresponding organisms for each product. The common product-to-creature reasoning modes can be classified as 'affective perception of product- affective perception of creature reasoning', 'product form- creature form reasoning', 'product function- creature function reasoning', 'product using environment- creature habitat reasoning' and 'product material-creature material reasoning'. When one reasoning mode refers to more than one creature, it is considered that the reasoning mode is used only once. Tables 1–5 show the main five reasoning modes, their frequency and examples. In addition, few subjects also used cultural association reasoning (four times), such as thinking of airplanes from tigers because of flying tigers.

Table 1. Affective perception of product-affective perception of creature reasoning (72 times).

Product	Creature	Reason
sofa	dog	The big dog that is close to people can be lean against, is big and gentle.
helmet	hippopotamus head	Hippopotamus head is very typical, honest and heavy, with a sense of security.
car	cheetah, tiger	We can find some brave but fast animals to design cars, such as cheetahs and tigers.

Table 2. Product form- creature form reasoning (49 times).

Product	Creature	Reason
airplane	eagle	Eagles often fly in the sky in a soaring posture, which looks more like an airplane in the air.
desk lamp	turtle	The shape of the tortoise shell is similar to the countertop at the bottom of the lamp.
Water cup	camel, pelican	The hump of a camel is like a container, and the beak of a pelican is very big like a container.

Table 3. Product function- creature function reasoning (34 times).

Product	Creature	Reason
desk lamp	lantern fish	From a functional point of view, first think of animals that can emit light. The lure of the lantern fish is luminous and has a ‘fishing rod’ structure, which is more consistent with a desk lamp.
speedboat	squid	Squids spray water backward and fast forward.
humidifier	whale	Humidifier and whale both can spray water.

Table 4. Product using environment- creature habitat reasoning (20 times).

Product	Creature	Reason
speedboat	dolphin, shark	Speedboats are in the water, I can directly think of aquatic animals like dolphins and sharks.
airplane	bald eagle,	Bald eagles live in the sky.

Table 5. Product material- creature material reasoning (19 times).

Product	Creature	Reason
motorcycle helmet	Snails, conch, pangolin	They all have very hard shell as motorcycle helmet.
sofa	rats, brown bear, tiger, orangutan, giraffe, kiwi	Sofa has the surface texture, which can imitate the fur and patterns of wild animals, such as brown bears, tigers, orangutans, and giraffes. Kiwi, because it has a special hairy appearance.

The reasoning from a creature to a product can contain more than one reasoning mode. For example, an eagle is chosen as a creature with an aircraft as a target product, and the reason is “The movement method of eagle and aircraft both is flying and the shape of eagle wings is similar to wings of aircraft.” It contains two reasoning modes: ‘product function-biological function reasoning’ and ‘product form- biological form reasoning’.

2.2. Study 2: Bionic Reasoning Experiment from Biology to Product

2.2.1. Subjects

A total of 12 industrial design graduate students, as in Section 2.1.1, were chosen as subjects to perform the bionic reasoning task.

2.2.2. Stimuli

Three experts discussed organisms to infer from trying to cover different types of creatures. Eight types of creatures were chosen: bald eagles, cheetahs, polar bears, jellyfish, beetles, cacti, elephants, and bees.

According to the research of Luo and Dong [23], providing subjects with textual descriptions of cultural relics can obtain more innovative solutions than pictures. To avoid

fixation in bionic reasoning, only the names of creatures are provided, and subjects are allowed to surf the internet.

2.2.3. Procedure

Based on eight biological samples, the participants were invited to deduce the related products of each creature as many times as possible through bionic reasoning and to describe the reason for each biology-to-product reasoning in short sentences.

2.2.4. Results

Statistics of the reasoning showed that, on average, each subject inferred 2.66 corresponding products for each creature. The creature-to-product reasoning modes can be classified as ‘creature form- product form reasoning’, ‘affective perception of creature— affective perception of product reasoning’, ‘creature function- product function reasoning’, ‘creature material- product material reasoning’, ‘creature culture- product culture reasoning’ and ‘creature habitat reasoning- product using environment’. Tables 6–9 show the main reasoning modes, their frequencies and examples. In addition, culture associations (five times) and environmental connections (three times) also occurred in biology-to-product reasoning.

Table 6. Creature form- product form reasoning (60 times).

Product	Creature	Reason
cactus	toothpick holder	The thorns are pulled out like toothpicks.
bald eagle	sickle	The outline is similar to the sickle.
elephant	excavator	The nose is shaped like an excavator. It is huge and heavy, similar to an excavator.

Table 7. Affective perception of creature— affective perception of product reasoning (58 times).

Product	Creature	Reason
polar bear	warm products	Polar bears look very warm and is suitable for designing quilts, scarves and hats.
bald eagle	high-end tea set	Bald eagle looks majestic and honorable.
cheetah	motorcycle	Cheetah is agile, fast and energetic.

Table 8. Creature function- product function reasoning (27 times).

Product	Creature	Reason
beetle	climbing aid	Beetles can climb on vertical branches or even glass because of the barbs and suckers on their feet.
bee	drone	Swarm collaboration, similar to drone fleet
cactus	water reservoir	Cactus born in the desert but can save many water.

Table 9. Creature material- product material reasoning (26 times).

Product	Creature	Reason
cheetah	camouflage	The cheetah’s skin has leopard print, which is easy to camouflage on the grassland.
jellyfish	umbrella	Jellyfish is transparent or transparent with color, it looks like an umbrella.
polar bear	sofa	Polar bear’s cortex looks advanced.

2.3. Discussion

As shown in Table 10, on average, each subject could infer 3.09 matching organisms for each product. Each subject could infer 2.66 products for each organism with an average level. When inferring from the target domain product to the source domain organism, the subjects' thinking is more open. This phenomenon could be explained by early-stage uncertainties in factors such as the product's form, material, affective perception, and so on, causing the learner to pick less-educated guesses than it does under the normal circumstance. In a real design situation, the reasoning space may become smaller as more target users and functions of products are determined. In reverse inference from the source domain organism to the target domain product, participants' ideas are relatively limited. After the experiment, some subjects mentioned that it was more difficult to think from creatures than products. This may be explained by the fact that products are familiar to subjects, but creatures are far from participants' daily lives, which contributes to different knowledge backgrounds.

Table 10. Comparison of biology-to-product and product-to-biology reasoning models.

Reasoning direction	Product to Biology	Biology to Product
Output quantity	Biology Avg = 3.09	Product Avg = 2.66
Reasoning mode and frequency	Affective Perception Reasoning (72) Form Reasoning (49) Function Reasoning (34) Environment Reasoning (20) Material Reasoning (19)	Form Reasoning (60) Affective Perception Reasoning (58) Function Reasoning (27) Material Reasoning (26)
Reasoning direction	Product to Biology	Biology to Product

The bionic mapping relationship between creatures and products is shown in Figure 2.

Figure 2. Bionic mapping relationship between creatures and products.

3. Methodology

Affective perception, function, material and habitat of creatures, as well as affective perception, function, material and using environment of products, can all be described in natural language. Meanwhile, biological form and product form can be better expressed through pictures.

This study introduces the bidirectional encoder representations from transformers (BERT) pretraining model to accomplish semantic reasoning of product BID.

3.1. Product and Biology Semantic Database

A biological description dataset and product description dataset are established by describing the affective perception, function, environment, and material of common creatures and products. Some of the data are shown in Tables 11 and 12.

Table 11. Biological description dataset (display part of data).

Name	Affective Perception	Function	Habitat	Material
giraffe	docile; elegant; beautiful; friendly	fight with the neck as a weapon; sleep in a standing position	grassland, shrubland, albizia woodland	short coat; variegated reticulation
dolphin	docile; friendly; cute; flexible	echolocation; good at jumping and snorkeling; swimming	ocean	smooth and hairless; sharp legs
owl	alert; funny; cute	night walking; strong night vision; eyes cannot turn in different directions.	tree; rock; grass; sky	soft feathers

All the descriptions are written in Chinese.

Table 12. Product description dataset (display part of data).

Name	Affective Perception	Function	Using Environment	Material
tank	large; hidden	reconnaissance; firing artillery; turret can rotate; advance slowly	jungle, grassland, desert	sturdy
ski board	fashion; cool	reduce the pressure on the gripping area on the snow	snow field	firm; smooth
hot air balloon	enthusiasm; lively	flying; the inside of the balloon heats the air and uses buoyancy to displace the whole	in the air	fire resistance; good airtightness; bright colors

All the descriptions are written in Chinese.

3.2. Product-Organism Semantic Similarity Calculation

The process of calculating the semantic similarity of sentences based on BERT is shown in Figure 3.

(1) Input Sentence

Input a product description sentence and a biological description sentence.

(2) Word Embedding

The BERT model converts natural language into mathematical representation through word embedding. Each word in the input sentence is expressed as a word embedding with a fixed length of m , which is convenient for subsequent processing and calculation.

(3) BERT Operation

After operation of the 12-layer transformer layer in the BERT model, the corresponding word embedding of the original sentence outputs. Suppose a sentence contains n Chinese words; then, the word vector output of the sentence is denoted as $\vec{f}_1, \dots, \vec{f}_n$.

(4) Sentence embedding calculation

Obtain the sentence embedding by calculating the mean value of the output word embedding. The sentence embedding is calculated as follows.

$$\vec{f} = \frac{\vec{f}_1 + \cdots + \vec{f}_n}{n}$$

(5) Cosine similarity calculation

Cosine similarity is used to calculate the similarity between two sentences. If the feature vector of sentence 1 is $\vec{A}$, the feature vector of sentence 2 is $\vec{B}$, the dimension of sentence embedding is m , and A_i and B_i are the components of $\vec{A}$ and $\vec{B}$, then the cosine similarity between the two sentences is calculated as follows.

$$\text{similarity} = \cos(\theta) = \frac{\vec{A} \times \vec{B}}{\|\vec{A}\| \times \|\vec{B}\|} = \frac{\sum_{i=1}^m A_i \times B_i}{\sqrt{\sum_{i=1}^m (A_i)^2} \times \sqrt{\sum_{i=1}^m (B_i)^2}}$$

The value range of similarity is $[-1,1]$. -1 means the two vectors are opposite, and 1 means the two vectors are the same. The greater the cosine similarity value, the higher the semantic similarity of the two sentences.

Figure 3. Product-organism semantic similarity calculation process based on the BERT pretraining model.

3.3. Semantic Reasoning of Product BID Based on BERT

When inferring creatures through products, first input the description sentences of the product, and the semantic similarities between the product and every creature in the dataset of each reasoning mode are calculated using the algorithm in Section 3.2. Finally, the creatures inferred from each category are sorted according to the similarity from high to low (Figure 4). Designers can choose creatures with high similarity as the source to start bionic expressions. It is similar to infer from creature to product.

Figure 4. Semantic reasoning process from product to biology.

3.4. Example

A bionic semantic reasoning system is developed on RoBERTa-wwm-ext, a derived Chinese model of BERT-base, which adapts whole word masking in the masked language model (MLM) pretraining task [24,25]. RoBERTa has been applied to text classification in many fields [26–29].

When using night light as the target product to search for suitable creatures for product BID, the designer first inputs descriptions of the night light, as shown in Table 13. The semantic reasoning results are shown in Figure 5 and Tables 14–17.

Table 13. Description of night light.

Affective Perception	fashion; warm
Function	illuminate
Material	light
Using Environment	in the room

All the terms are written in Chinese.

Figure 5. Bionic night light design reference, concept sketch and rendering effect.**Table 14.** Semantic reasoning result of affective perception.

Inference sentence: fashion	
Result	(‘ fashion ’, [Flamingo]), (‘ handsome ’, [bald eagle, zebra, cheetah]), (‘ light ’, [jellyfish, butterfly]), (‘ elegant ’, [giraffe, emperor penguin, cheetah, red-crowned crane, swan, puppet cat]), (‘ sexy ’, [hippo])
Similarity	[1.0000000, 0.7545206, 0.7223246, 0.7198027, 0.7121808]
Inference sentence: warm	
Result	(‘ warm ’, [polar bear, giant panda, sunflower]), (‘ homesick ’, [emperor penguin]), (‘ docile ’, [African elephant, giraffe, dolphin, lop-eared rabbit, sheep, pig, puppet cat]), (‘ friendly ’, [pigeon, golden retriever, puppet cat]), (‘ lazy ’, [puppet cat])
Similarity	[0.8465299, 0.7907890, 0.7823601, 0.7615751, 0.7563425]

All the terms are displayed in Chinese.

Table 15. Semantic reasoning result of function.

Inference sentence: illuminate	
Result	(‘ glow ’, [jellyfish]), (‘ strong night vision ’, [owl]), (‘ phototaxis ’, [praying mantis]), (‘ active at night ’, [bat]), (‘ night walk ’, [owl, tiger])
Similarity	[0.7271294, 0.709383, 0.7041074, 0.6780104, 0.6738881]

All the terms are displayed in Chinese.

Table 16. Semantic reasoning result of material.

Inference sentence: light	
Result	(‘ light ’, [jellyfish]), (‘ supple ’, [golden retriever]), (‘ soft ’, [puppet cat]), (‘ smooth ’, [orca, beetle, ant, bamboo]), (‘ fluffy ’, [ostrich])
Similarity	[1.0000000, 0.8214510, 0.7871054, 0.7731293, 0.7605499]

All the terms are displayed in Chinese.

Table 17. Semantic reasoning result of using environment.

Inference sentence: in the room	
Result	(‘in the air’, [bee, red-crowned crane]), (‘sky’, [bald eagle, owl, flamingo, woodpecker, pigeon]), (‘on the tree’, [woodpecker]), (‘desert’, [camel, cactus]), (‘ocean’, [jellyfish, killer whale, dolphin])
Similarity	[0.7273592, 0.6848752, 0.6745558, 0.6739956, 0.6695887]

All the terms are displayed in Chinese.

According to the inference result, jellyfish ranked first in function reasoning, and the function description “illuminate” of night light corresponds to “glow” of jellyfish’s function. At the same time, jellyfish also ranked in the top five in environmental reasoning and affective perception reasoning. Therefore, jellyfish was chosen as the source domain creature of the night light.

The designer searched for more jellyfish pictures for reference, drew the conceptual sketches, performed modeling and rendering in the 3D modeling software Rhinoceros, and finally completed the product shape bionic design of the jellyfish night light (Figure 5).

4. Discussion and Conclusions

This study first conducted two experiments to determine designers’ bionic reasoning thinking in top-down and bottom-up processes and obtained bionic mapping relationships, including affective perception, form, function, material and environment. Based on the reasoning modes, the NLP pretraining model BERT was used to assist the bionic semantic reasoning. Sentence-level fuzzy semantic reasoning of product-to-creature and creature-to-product can both be realized.

The advantages of this method are listed as follows.

(1) Through experimental research, designers’ bionic reasoning thinking modes such as affective perception, form, function, material, and environment are obtained. Comparing with the previous bionic reasoning, which lacks research on real reasoning thinking, the applied methodology simulates designers’ real ideation in product BID, which makes bionic semantic reasoning more comprehensive and scientific.

(2) Unlike the keyword-based precise reasoning in the past, the usage of BERT in bionic reasoning helps achieve sentence-level fuzzy search in BID for the first time. Moreover, comparing with perception matching, the applied methodology does not require much labor on manual scoring, which improves the search range and efficiency of bionic reasoning.

(3) During the study, the researchers have built two scalable datasets, including a biological description dataset and a product description dataset, and both can serve as a foundation to broaden designers’ bionic reasoning thinking and knowledge, which will be helpful for product BID education and industry.

Future works of this article are listed as follows.

(1) First, work is the improvement of the datasets. Data in the biological dataset and product dataset are limited; therefore, the final reasoning similarity is not extremely high. Meanwhile, this study uses manual methods to get data instead of crawling because the data required are relatively special. In the future, we will expand the dataset and look for ways to automate the sourcing process.

(2) At present, the reasoning results under each reasoning mode are displayed independent of one another. One creature can be recommended by two different modes at the same time. Thus, a comprehensive recommendation system based on weights assigned to different modes is a potential future project to develop. At the same time, morphological reasoning and topological reasoning mentioned in Section 1.2 can also be included.

(3) At last, this semantic reasoning method can be applied in other analogy design fields, such as cultural product design, which takes cultural artefact as the source domain and product as the target domain.

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