Design by Analogy: A Proposed Model

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***Abstract*—This paper introduces a new model of Design by Analogy (DbA) and demonstrates its applications to a smart bed for preventing the elderly's falls. Integrating three theories of analogy together, the model describes design processes as a recursive procedure of discovering the problem, defining the analogy target, searching for the analogy sources, blending the target and sources, and approving the blended concepts. The model has advantages in explaining the existing cases of product innovation resulted from DbA, and in generating innovative product concepts in a systematic way. The application of the model could be universal, including product, user interface and user experience design, service design, and business model design. Further investigation on similarity measurement methods and more applications could verify the effectiveness of the model.**

***Index Terms*—industrial design, design by analogy, design creativity, innovation, design methods**

I. Introduction

Analogy thinking is the key to human creativity [1-3] and plays an important role in design. Schön [4] illustrates a case of a synthetic paintbrush from a designer's perspective. Trying to replicate the bristles for a period of time, a group of product development researchers was unable to design a synthetic brush that did not produce discontinuous gloppy painted surfaces. Once, a member of the team found a breakthrough: '"A paintbrush is a kind of pump." This analogy, or so-called "generative metaphor" in [4], led the team turn to focus on the channels between the bristles, and help the team to generate new perceptions, explanations, and inventions.

Although careful comparisons between analogies and metaphors have been made in the literature (e.g., [5]), the present paper ignores the difference because it does not cover the implicit meaning created by metaphor. Design using analogy can assist designers to solve "wicked problems," which are impossible to well define for their incompletion, uncertainty, contradiction, and continually changing in essence (see [6]). When the designer's logical reasoning or propositional knowledge does not work for solving a new problem during ideation stages, he or she may search for something similar in certain aspects to adapt or modify them into a creative solution for the new problem.

Many theoretical models of such kinds of analogy have been developed [7], yet few of them are applied to design methods for practice. The major objective is to propose a new model of Design-by-Analogy (DbA) for designing creative products. The remainder of this paper is organized as follows. The next section reviews three related models and theories, and the third section presents the new model. In the fourth section, the application of the new model to a product and a service are introduced. The conclusions of this study are drawn in the fifth section.

II. Related Work

DbA is the process of generating solutions for design problems through the mapping of features that a source problem may share with an existing target solution [8]. There is a range of available analogy theories, in which three convincing ones, namely, Structure-mapping Theory (SMT), Feature Salience Imbalance Theory (SIT), and Concept-Knowledge Theory (C-K Theory) are reviewed as follows.

A. Structure-mapping Theory

Gentner [9] proposes Structure-mapping Theory (SMT) that describes human being's implicit limitations in interpreting analogies and similarity. In the SMT, an analogy is a mapping of knowledge from one domain to the other domain based on the similarities of features and the similarity of the relations among the features (also called structure). A domain refers to any object (e.g., the sun, a tree, or a chair) or concept (e.g., love, speediness, or power). Take the above analogy, "A paintbrush is a pump" for example. The target domain, "pump," is mapped onto the source (also called base) domain, "paintbrush." The mapping is, by definition, a cognitive process that builds the structural alignment between two situations to further reasoning.

The two similarities of features and relations construct a map of four major categories to locate comparisons between any two domains. If the common feature and relation are similar, the comparison is "literal similarity." On the contrary, if the common feature and relation are dissimilar, it is "anomaly." If the common feature is similar but the relation is dissimilar, it falls into the category of "mere appearance". Finally, a comparison is called "analogy" if the common feature is dissimilar but the relation is dissimilar [10].

For example, "My job is a jail." is an analogy, because "my job" and "jail" share dissimilar features but share similar relations that somebody's movements or actions are restrained physically or psychologically in a certain

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space for a certain time. From the perspective of creativity, SMT prefers the analogy to mere appearance or literal similarity, and avoid anomaly.

B. Salience Imbalance Theory

Improving the symmetric similarities measured in Tversky's [11] Contrast Model (CT), Ortony [12-14] proposes Salience Imbalance Theory (SIT). For example, "My job is a jail." conveys a different meaning form "A jail is my job."

As the similarity perceived by the human being is asymmetric by nature, the salience of the common feature shared by the target and source sorts four types of the similarity [15]. The first type is "literal similarity," where the common feature is equally salient for the target and the source, the comparison. The second type is "metaphorical simile," where the common feature is more salient for the source than the target. The third type is "reversed simile," where the common feature is, on the contrary, more salient for the target than the source. The fourth type is "anomaly," because the common feature is not salient for the target and the source.

Take "My job is a jail." for example, again. Generally speaking, the common feature that one imposes extreme constraints on another is more salient for the source, "jail," than the target, "my job." Thus, "My job is a jail." is a metaphorical simile. In the viewpoint of figure speech, SIT suggests metaphorical simile rather than mere appearance or literal similarity, and avoid anomaly.

C. Concept-Knowledge Theory

To understand the co-expansion of concepts and knowledge in designer' thinking at ideation stages, Hatchuel [16] proposes Conceptual-Knowledge Theory (C-K Theory) as a transdisciplinary language. In C-K Theory, a design is a process of transforming concepts into knowledge. In terms of logic, the knowledge refers to propositions, whose truth value is decidable, while the concepts refer to undecidable propositions. A design process starts with the disjunctions from some knowledge to generate initial concepts, and ends up at the conjunctions from the approved concepts to add new knowledge into existing knowledge base as well as the reasoning of the available knowledge to create new solutions [17, 18].

The design process comprises four operations. The first operation, K→C, is the disjunction by adding or deleting features from some knowledge in the knowledge space to compose concepts in the concept space. The second operation, C→K, is the conjunction by composing features of some concepts, followed by testing their "truth value" (e.g., technical feasibility or empirical validity) in order to compose knowledge. The third operation, C→C, is the partition and inclusion of existing concepts to expand the concept space. The fourth operation, K→K, is the deduction of the existing knowledge to expand the knowledge space.

C-K Theory provides a concise rationale of discovering and defining problems, developing concepts, and approving and delivering concepts. The co-expansion of knowledge and concepts support the blending of source and target to result in a good analogy. The above theories provide useful guidelines for design by analogy. The next section introduces a new model based on the three theories.

III. The Proposed Model

Fig. 1 illustrates the new model of DbA, consisting of the target space and source space. The source space contains the existing knowledge, K, represented in rule-based knowledge, frame-based knowledge, case-based knowledge, semantic network, and so on. In particular, CB knowledge plays a key role in the model because the process of DbA is similar to case-based reasoning. In contrast, the target space contains the concepts, i.e., undecidable propositions to be approved. In the model, the design process is divided into five steps as follows.

A. Discovering the Problem

A problem, P, is the proposition discovered by examining the inconsistency in existing knowledge, K, or between the observed facts and K. For example, our K about the existing blind canes may indicate the need of automatically detecting objects in the path and guide the path of the visually impaired people. The case base (CB) containing abundant exemplars related to visual impairment provides useful case-based knowledge for finding their pain points. Each case contains a pair of a problem and its solution and is represented in terms of the source category, SC, and the source object, SO.

B. Defining the Target

The analogy target (i.e., the design objective) is defined by operating disjunctions from the problem, P. The target is represented in terms of the target category, TC, and the target object, TO. For example, the need of automatic guide for the visually impaired may be described as the requirements of a new blind cane which can automatically guides the user's walking paths to prevent from danger, and belonging to the "Health & Household" category.

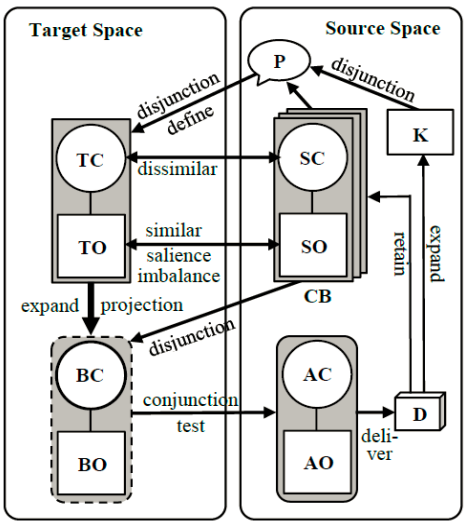

Figure 1. The proposed model of DbA.

C. Searching for the Sources

The candidate sources for DbA are searched by comparing the target and sources. The principles include the minimal similarity of categories (*diss*), the maximal similarities of features and structure (*sim*), and the feature salience imbalance from the source to the target (*sit*). For example, a certain drone with a three-axis guide system could be a good source, because it shares the common structure about the movement control of the target, but belongs to a rather different category, "Toys & Games" category. According to SMT, this example is an analogy because they share similar structure but different feature about appearance and functions. According to SIT, it is a metaphorical simile since the features about autopilot is obviously more salient for the drones than the blind canes.

D. Blending the Target and Sources

Once some good sources have been acquired, they are blended with the target together to develop new concepts, represented in terms of the blended category, BC, and blended object, BO. The blending involves two projections: the disjunctions from the sources and the expansions of the initial or existing concepts. There are three types of the blending based on the features and structure. First, if the source's features and/or structure occupy the majority in the projection process, it is called a source-oriented blending. Second, if the target's features and/or structure occupy the majority, it is called a target-oriented blending. Third, if the "emerging" features and/or structure occupy the majority, it is called emergence-oriented blending.

In a blending, for example, the drone's features about appearance and its structure about product architecture account for a large proportion in blending. Only the blind cane's feature of handle remains, while the other features about the stick-shape and the relations among the handle, stick and cane tip have been omitted. Hence, this blending is, by definition, source-oriented.

E. Approving the Concepts

When a new concept has been created by blending the target and source, its feasibility is tested by means of functional prototyping, usability, aesthetics evaluation, etc. If a concept is technically feasible or empirically valid in the conjunction process, it is seen as an approved concept, represented in terms of the approved category, AC, and approved object, AO. The approved concept becomes a new knowledge in the source space.

For example, the winner of iF Design Talent Award 2018, "Guidrone," is a drone as a leading hand with autonomous navigation to help the visually impaired become more independent. The concept is approved by the jury because it is ergonomic and has a high practical benefit for the target group [19].

IV. Application

Falls are a major cause of morbidity and mortality in elderly people, but few products can effectively prevent the falls. This section shows the application of the proposed model to a smart bed design, "Transformer," for preventing the falls. The DbA process is illustrated in Fig. 2, and the detail is described as follows.

A. Discovering

According to a survey [20] in Taiwan, one in five people over 65 years of age fall at least once a year. Moreover, a high rate of hip fractures occurs as a result of falls, and the mortality rate for falls increases dramatically with age. Various interventions, including the modification of environmental hazards and the evaluation and treatment of blood pressure, vision problems and mental status changes, to prevent falls are effective to a certain extent [21]. However, there are few solutions focusing on the bed falls in the elderly in household environments, mainly caused by postural hypotension. This problem is discovered based on the design team members' knowledge from literature reviews, interviews with the elderly (see Fig. 3, left), and personal experience.

B. Defining

By selecting some pieces of the team members' knowledge in brainstorming workshops (see Fig. 3, right), the discovered problem is defined as the analogy target. Besides the features of a typical bed (e.g., shape and size), the target features include non-medication approaches to behavioral aids, such as the prediction of user intention to get up and the immediate supports for ankle pumps or hand clenching and elevation of the head of the bed. The target structure contains the interactions between the elderly and the bed, such as the mechanisms for supporting user behaviors. The target category is defined as "Home & Kitchen."

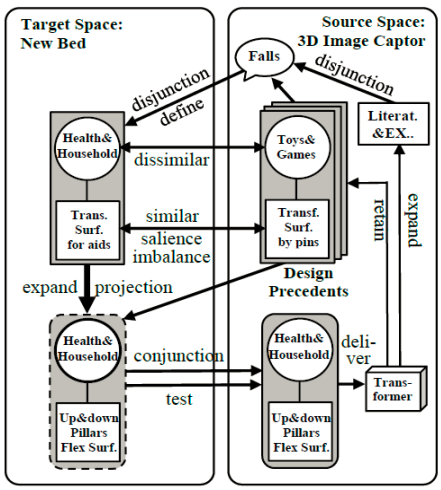

Figure 2. The proposed model of DbA.

C. Searching

The designers begin to compare hundreds of objects with similar features, similar structure, and higher feature salience imbalance out of the "Home & Kitchen" category. The above principles of a good analogy are used to select better sources. After reviewing each object, the selected sources involve electric wheelchairs, care robots, medical air bubble mattresses, and 3D image captors (see Fig. 4, left).

D. Blending

The designers draw a number of sketches to develop as many ideas as possible by means of source-oriented blending, as shown in Fig. 4, (right). Among these sketches, a convincing idea is to adopt the mechanism of the pin's linear movement in the 3D image captor into the bed structure. First, the category similarity between of "Health & Household" and "Toys & Games" is relatively low. Second, the blending is of analogy because the designed bed and the 3D image captor exclusively share the common structure of transformable surface. Third, since the salience imbalance of the structure is higher for the 3D image captor, the blending is metaphorical simile.

As illustrated in Fig. 5 (left), the new bed consists of 18 by 10 pillars with the structure similar to the 3D image captor. As soon as the elderly' intention of getting up is predicted, the flat bed-top surface transforms to various shapes, in sequence, for aiding ankle pumps, warm-up exercises, elevation adjusting, and hand clenching.

In addition, the feature of pressure sensors in body weight scales emerges in the blending for collecting data of the elderly's posture to predict their intentions. Finally, the development of this idea is a process of source- and emergence-oriented blending.

E. Approving

Fig. 5 (right) shows the prototyping of the blended concept to test its technical feasibility. The pressure sensing module is built in the pillar tops to transmit the data to the analysis module for behavioral predictions. Fig. 6 depicts the scenario. The first scene shows an old man sleeping in the bed. In the next scene, the bed detects that he moves and change posture before getting up. In the third scene, some pillars move up and down to help him do ankle pumps and warm-up exercises for a while. The final scene shows some pillars move vertically to form an armchair-like shape to help him clench the handles while getting up. The smart bed design is the winner of Best Design Award, organized by the Ministry of Science and Technology, Taiwan, for its innovation and commercialization potential.

Figure 3. Interviews (left) and brainstorming (right).

Figure 4. The 3D image captor (left, adapted from [22]) and idea sketches (right).

Figure 5. The detail (left) and prototyping (right).

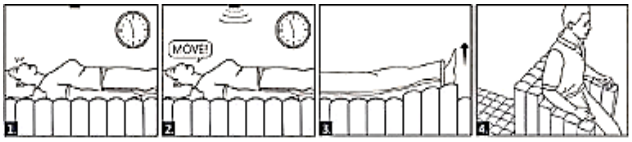

Figure 6. The scenario.

V. Conclusions

The present study integrates three theories related to analogy to propose a new model of design by analogy and demonstrates its application to a smart product design. This provides a good starting point for developing new theories of DbA.

The proposed model describes the design process as a recursive procedure of discovering the problem, defining the analogy target, searching for the analogy sources, blending the target and sources, and approving the blended concepts. It also provides with a set of useful guidelines to generate new concepts from the source space and, in turn, to add the approved concepts as new design precedents to the source space. The model has advantages not only in explaining the existing cases of product innovation resulted from DbA, but also in generating innovative product concepts in a systematic way.

The operation of the model is simple and straightforward for designers, students, and even novices to apply to practice. Moreover, the applications of the model could be rather universal, including user interface and user experience design, service design, and business model design. Further investigation on similarity measurement methods and more applications could verify the effectiveness and usability of the model.

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