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COMPUTATIONAL SUPPORT OF DESIGN CONCEPT GENERATION THROUGH INTERACTION OF SKETCHING, ONTOLOGY-BASED CLASSIFICATION AND FINDING VOIDS

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Abstract

Drawing a sketch takes an important role for generating new design concepts. Although there are some tools that can support the drawing activity, designer's thinking process behind it has rarely been supported, because its process is implicit, and therefore, it is difficult to explicitly formalize it. This research focuses on the concept generation process through interaction of sketching and classifying concepts, and proposes a computational support methodology that helps a designer systematically find new concepts which cannot be noticed intuitively. This methodology consists of three steps, i.e., representing design concepts with sketching, classifying concepts with the function ontology, and finding new design concepts with the void theory that sees design concept generation as a process to resolve defects of the classification. A prototype support tool is implemented based on the proposed methodology. This paper demonstrates a concept generation example performed with the prototype support tool to show that more design solution candidates can be created with the proposed methodology.

Keywords: Conceptual design, Creativity, Design methods, Sketch, Concept operation

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1 INTRODUCTION

Generation of new concepts in product design process serves as driving force of innovation. Many researchers in design engineering domain have tackled to build theories and methodologies of design concept generation so that its process can be carried out in a systematic way. When reflecting on the nature of concept generation, most design theories including the systematic approaches associate it primarily with words or with language (Schön and Wiggins 1992). Some researchers have focused on the role of sketching activity in design concept generation. Researches of design protocol analysis have revealed that concept generation process is carried out by reflective interaction between verbal and drawing expression (Yang and Cham 2007). Designers notice concepts implied by drawing expression, clarify those by verbal expression, and then develop ideas through the interaction. Concept operation behind the interaction process takes a crucial role for stimulating creativity. However, it has rarely been supported with a computer tool, because its process is done in designer's implicit thought, and therefore, it is difficult to explicitly formalize.

This paper states the authors' position for the above issues focusing on interaction between concept operations and sketching activities behind design concept generation, and proposes a computational support methodology that helps a designer systematically find new concepts which cannot be noticed intuitively. This methodology consists of interactions of three steps, i.e., representing design concepts with sketching, classifying concepts with a function ontology, and finding new design concepts with void theory (Tomiyama et al., 2010) that sees design concept generation as a process to resolve defects of the classification. A prototype support tool is implemented based on the proposed methodology. A simple case study is shown to demonstrate its validity and possibility. This paper also discusses our future works.

2 THEORETICAL BACKGROUND OF CONCEPT GENERATION SUPPORT

2.1 Sketching in Concept Generation

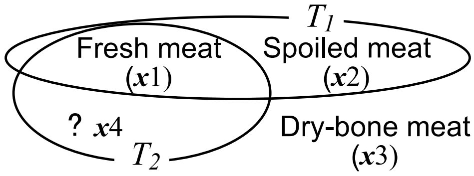
In this research, sketch means a draft of an idea of design concepts. It includes adding keywords to an idea. Some researchers have focused on the role of sketching activity in design concept generation. Researches of design protocol analysis have revealed that concept generation process is carried out by reflective interaction between verbal and drawing expression. For example, Suwa and Tversky (1997) state that sketches help designers get unanticipated findings, reinterpret ideas and create new design requirements. Design experiments performed by Yang's research group shows that some attributes of sketching activity, such as quantity of sketch, carefulness, plainness, timing and duration of sketching effect on design outcomes (Yang and Cham, 2007, Yang, 2005, 2009).

Those prior works focus on roles of sketch in early stages of engineering design and designer's thinning process behind sketching. Although they don't discuss about its computational support, their findings give knowledge for implementation of a computational support tool.

2.2 Concept Operation

Design engineering community has addressed the formalization of the design concept generation process, and proposed methodologies supporting it in a computable, structured, and rigorous, not ad hoc manner (Antonsson and Cagan, 2010). In its systematic approach, a classification system of generated concepts takes an important role to help designers think logically and create new concepts. General Design Theory (GDT) (Yoshikawa, 1981) models design process as concept operations, i.e., set operational processes regarding the entity set and its subsets. The following anecdote clarifies the role of concept operation. Let us consider a primitive world, where only three kinds of meat are found, fresh meet, spoiled meet, and dried meet; all natural entities, without any artificial processing. As shown in Figure 1, people of the world recognized and memorized them as natural entities; x_1 = fresh meat, x_2 = spoiled meat, x_3 = dry-bone meat. People in the world construct concepts about peculiar characteristics abstracted from these entities, which are called abstract concepts, giving classifications from the viewpoint of function or value of the entity. For example, let $T = \{T_1, T_2\}$ be a classification: T_1 = {changing with lapse of time}, T_2 = {eatable} as shown in Figure 1. It is assumed that people had the ability of logical operations such as disjunction, conjunction, or complement besides memory, abstraction and classification. Someday, a person in the primitive world thought accidentally about; $\overline{T_1} \cap T_2 = \emptyset$. This combination leads to a defect of the classification, called *void*

(Tomiyama et al., 2010). This had no correspondence to a real entity but the value of it was higher than any existing entity. "Eatable and not change with lapse of time" had the highest value, and this conceptual combination was the necessary condition to invent the smoked meat (x_4) which had been the first artificial entity for the human beings.



$T_1 \quad = \{x \mid x \text{ is changing}\}$

$T_2 \quad = \{x \mid x \text{ is eatable}\}$

Figure 1. Design Concept Operation

The above simple anecdote implies that it is critical to have an image about specifications that have no immediate solutions. This is a necessary condition for creative design. The empty set in the classification system correspond to design solutions that never existed before.

A classification system is gradually updated through design process. It might include some defects of classification, e.g., a defect that any abstract concept is missing to classify multiple entities which belong to the same set, and a defect that an entity concept is not classified to any abstract concept. This research calls the former a *redundant* entity, and the latter an *unclassified* entity. Those defects shows that more abstract concepts can be extracted from the set of entites. Resolving those defetcs enable to find more voids, and then to generate more new ideas.

2.3 Function Ontology for Conceptual Design

When reflecting on the nature of designer's thinking, most design researches associate it primary with words or with language (Schön and Wiggins 1992). Function is a conventional research topic of the word or language approach. Pahl and Beits (2007) method, a representative systematic approach of design, defines that a conceptual design phase consists of defining a required function, developing it to sub functions, exploring alternative principles to realize the sub functions and combining the alternative principles to get design solution candidates.

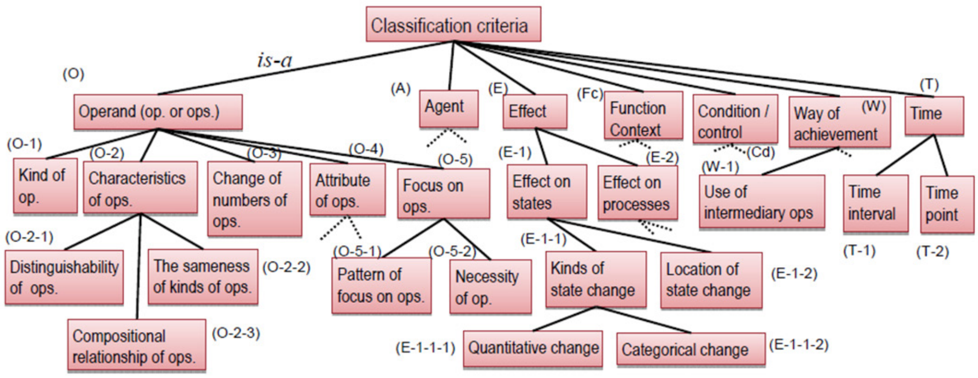


Figure 2. Function classification criteria (portion) (Kitamura et al. 2011)

Function ontologies have been developed for support of building function hierarchy steps in conceptual design, e.g., Hirts et al., (2008) and Kitamura and Mizoguchi (2013). A function ontology provides terminology of function such that designers can avoid wording inconsistency. However, it lacks ability to explain rationale of a function classification. It would lead incomplete function development. Function classification criteria (Kitamura et al., 2011) has been developed to clarify rationale of super-sub relation in function ontology. Figure 2 shows a portion of function classification criteria. For example, 'transfer' in a function ontology can be classified into 'transport' and 'transmit' based on the criterion *kind-of operand* (O-1) according to the values "material" and "energy", respectively. It shows that those two sub functions differ in a transferred object. Note that a function is denoted with ‘’, a function classification criterion in italic text and an operand of function with “”.

2.4 Research Issues and Approaches

As stated in Subsection 2.1, sketching is a quick way to represent ideas that cannot be verbally express, and to promote a designer find new concepts in verbal expression. However, association between drawing expression and verbal expression is often implicit. It can be rarely performed in a systematic way. On the contrary, a void theory suggests a systematic approach to generate new concepts based on the classification. A function classification criteria with function ontology is a systematic way to classify function concepts. Those two are considered as complementary to sketching activity for systematic process of design concept generation, and for its computational support.

First, this research proposes a new systematic methodology of design concept generation with interaction of the three different approaches, i.e., sketching, function classification criteria, and void theory. Figure 3 shows its overview: (i) ideas are expressed with sketches, (ii) sketches are classified with a function ontology, (iii) voids are found based on the classification, and new ideas corresponding voids are expressed with sketches. The authors’ prior work (Nomaguchi, et al., 2013) proposes a methodology to integrate sketching and a void theory. This research augments function classification criteria approach to it, and propose comprehensive interaction of them.

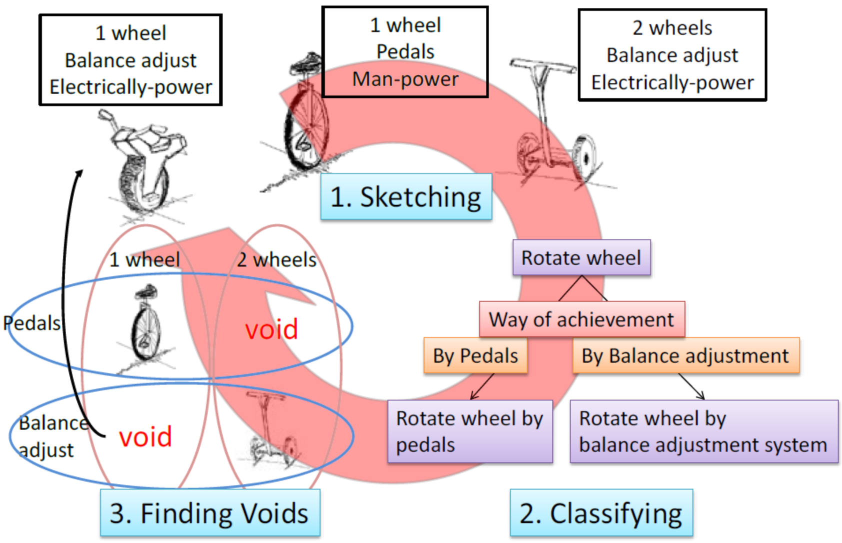


Figure 3. Interactions of sketching, classifying and finding voids

3 INTERACTION OF SKETCHING, ONTOLOGY-BASED CLASSIFICATION AND FINDING VOIDS

Although the three activities generally proceed in the order shown in Figure 3, back-and-forth interaction between each couple of activities; interaction of sketching and classification, interaction of classification and finding voids, and interaction of finding voids and sketches. The following subsections explain the details with an example of ride-on toy design in Figure 3.

3.1 Sketching and Classification

As stated in Subsection 2.3, function classification criteria have been developed originally for clarifying rationale of super-sub relation in a function ontology. This research adopts it for supporting design concept generation. A designer can systematically find verbally-expressed concepts from drawing expression with a terminology in a function ontology, and systematically classify ideas with function classification criteria.

In an example of Figure 3-1, a designer first draws two sketches: a monocycle and a two-wheeled, self-balancing, battery-powered electric vehicle, looks like a Segway. A designer finds common functions for the two ideas, i.e., ‘to rotate wheel’ and ‘to drive’, and their different values “by pedals” and “by balance adjustment system”, and “with one wheel” and “with two wheels” (Figure 3-2).

3.2 Classification and Finding Voids

Each element in sketching activity can be linked to the GDT framework stated in Subsection 2.2 by the following mapping. A sketch representing an idea can be seen as an entity concept. A verbal expression representing features of ideas can be seen as an abstract concept. A function is an abstract concept that represents requirements or characteristics of design concepts. Any operations on sketch and verbal expression can be seen as logical operations on entity concept sets. A classification system of design concepts corresponds to a classification of sketches. A space that there is no correspondence sketch is a void. In an example of Figure 3-3, a classification system suggests two voids, i.e., “one wheel” $\cap$ “by balance adjust” and “two wheels” $\cap$ “by pedals”.

3.3 Finding Voids and Sketching

A void is a trigger for designer for thinking a new idea. A designer draws sketches of generated ideas. Then, a new round of the interaction of the three approaches begins. Iterating the interaction can help a designer perform systematic design concept generation. In an example of Figure 3-3, a designer focuses on a void of “one wheel” $\cap$ “by balance adjust”, and generate an idea of one-wheeled, self-balancing, battery-powered electric vehicle.

3.4 Requirements toward Computational Support

A computational tool for supporting design concept generation is required to cover the above three interactions. This research summarizes the following requirements to meet the requirement.

1. For interaction of sketching and classification, a support tool should have a mechanism of representing both verbally expressed concepts, which used for representing a classification system, and drawing expression of design solution ideas, and a mechanism of providing function classification criteria.
2. For interaction of classification and finding voids, a support tool should have a mechanism of browsing of multiple sketches based on a classification system, and resolving defects of classification and finding voids.
3. For interaction of finding voids and sketching, a support tool should have a mechanism to flexibly adding sketches to a classification system.

4 TOOL IMPLEMENTATION

4.1 Prototype System

This research implements a prototype system to meet the requirements noted in Subsection 3.4. Figure 4 shows an overview of a prototype system. It is implemented by object-oriented programing language Java (SDK 6.0) on Windows 7. WACOM LCD tablet DTU-710 is used in order to input drawing expression by pen gestures. A framework of DRIFT (Nomaguchi and Fujita, 2013, Nomaguchi, *et. al*. 2013) is adopted for integrating some tools and managing design process.

A support system has a front end of a drawing tool and a concept tree tool which represents classification system of design concepts (Figure 4-(1)). A data base of function ontology and function classification criteria (FCC) (Figure 4-(7)) is equipped with a concept tree tool so that a designer can refer them while he/she operates a classification system. The framework employs a concept network model (Figure 4-(2)) as a generic form of design representation. The concept network model associates a drawing expression with each design concept represented in verbal expression. Common object classes for integrating tools is defined (Figure 4-(3)), i.e., classes of verbal concepts such as function, entity attribute and hierarchy, and classes of drawing expression such as sketch, draw layer and draw line. Those features meet the requirement 1 in Subsection 3.2.

The core of DRIFT framework is the three-layered process model shown in Figure 4-(4). The framework realizes recording of the design process as a byproduct of the natural design activities that is performed on a concept tree tool and a drawing interface, and management of alternatives of a concept tree and a sketch. A classification table browses a classification system with two axis concepts selected by a designer. It is implemented on a front end of design process management system (Figure 4-(6)). It displays alternative sketches related to a design concept of entity or function, which are captured by the three-layered model, and automatically organizes them into a table format. This research assumes that a classification system of design concept would be incomplete in design process, and it contains defects such as redundant and unclassified sketches. A function ontology and FCC (Figure 4-(7)) also work for it. A designer can refer terminology and classification criteria to update a classification table. Those features meet the requirement 2 in Subsection 3.2.

A designer can find voids on a classification table, and draw a sketch corresponding a void on a drawing tool. This feature meets the requirement 3 in Subsection 3.2.

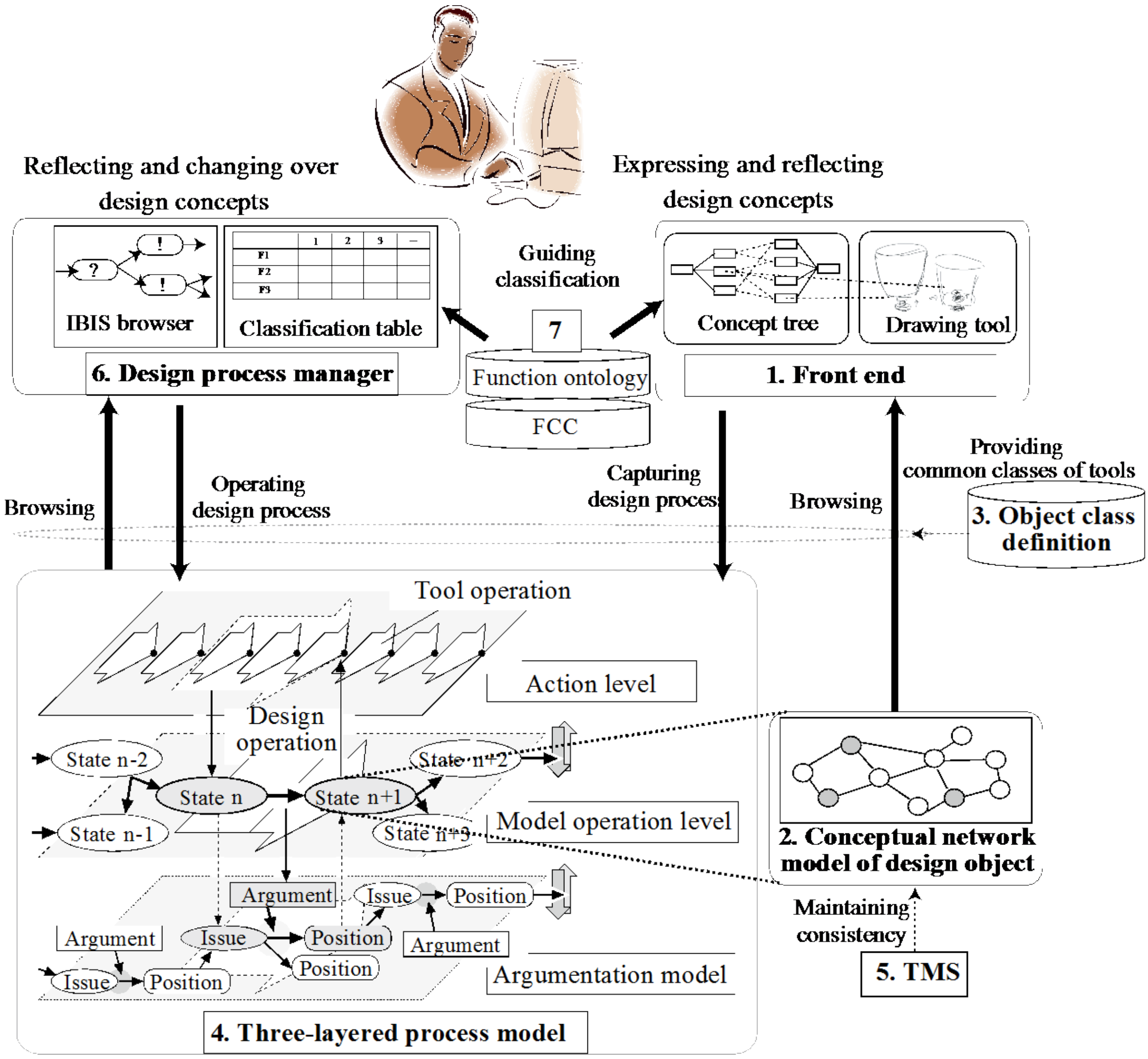


Figure 4. Overview of design concept generation tool based on DRIFT

4.2 Design Example of Easy Carrier

This subsection demonstrates an example case of design concept generation of a new easy carrier for baggage performed on a prototype system.

4.2.1 Representing Ideas with Drawing and Verbal Expression

First, a designer draws initial ideas that are called to mind by verbal expression 'to easily carry baggage' (Figure 5). Some abstract concepts classifying those ideas can be found, e.g., a way of carrying: "on a cart" (1-6) or not (7), a way of moving a cart: "by pushing" (2, 3, 6) or "by pulling" (1, 4, 5), a way of supporting baggage: "in a large bag" (3, 4, 5, 6), "on a rack" (1, 2), and so on. Those abstract concepts are express verbally and associated with sketches.

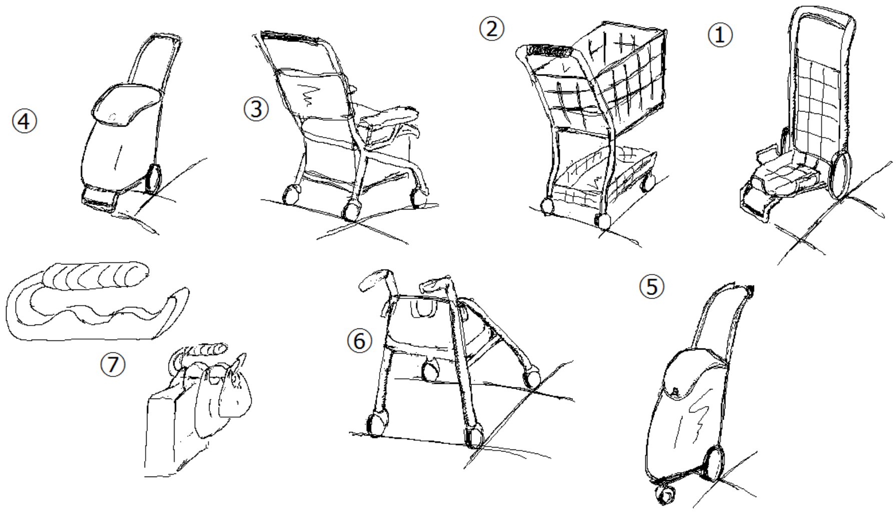


Figure 5. Initial idea sketches

4.2.2 Idea Classification with Function Ontology

An FCC database is used to clarify an abstract concept that is a key of classifying concepts and rationale of classification. In this design example, a classification with a way of supporting baggage is recognized as one focusing on *vehicle-of-operand* of a function 'to support baggage' according to the values "in a large bag" or "on a rack". Another classification of "by pushing" or "by pulling" is recognized as one focusing on *way-of-achievement* (*W* shown in Figure 1) of a function 'to carry baggage on cart'.

4.2.3 Concept Operation on Classification Table

A classification table is used to browse a classification system and its defects with two axes concepts selected by a designer. The classification criteria and the values that a designer refereed are also displayed on a table. Figure 6 shows a classification table with two axes of 'to support baggage' (vertical axis) and 'to carry baggage on cart' (horizontal axis). A red text denotes a selected classification criterion. A blue text denotes a value of the classification. Sketches are automatically placed on the corresponding category.

A table of Figure 6 shows that there are four redundant sketches and one unclassified sketch in the classification, and no void is found. The FCC database is referred again to resolve those defects. In this example, a designer focuses on a cell of "to support baggage by bag" and "to carry baggage on cart by pulling", which contains two redundant sketches (Sketch 4 and 5). An FCC *kind-of-state-change* (E-1-1 in Figure 2) suggests a new classification for them: "carrying in standing position" (Sketch 5) and "carrying in inclined position" (Sketch 4). Those concepts can classify the two sketches and resolve the redundancy. As for the unclassified sketch (Sketch 7), a designer refers an FCC *compositional-relationship-of-operand* (O-2-3 in Figure 2) and notices that a design alternative drawn in Sketch 7 supports baggage "from above", while the other design alternatives support baggage "from the bottom". Figure 7 shows a revised classification table that all redundant and unclassified defects are revolved.

4.2.4 Finding Voids and Generating New Ideas

A revised table of Figure 7 suggests nine voids that cannot be found in an initial classification table. A designer can generate new ideas corresponding to them. Figure 8 shows one of new ideas generated for a void cell of 'to carry baggage on cart by pulling in standing position" and "to support baggage from above". This new carrying tool has hooks for hanging several bags. Because it has a simple structure, it can be so light weight that a user can easily carry with small force.

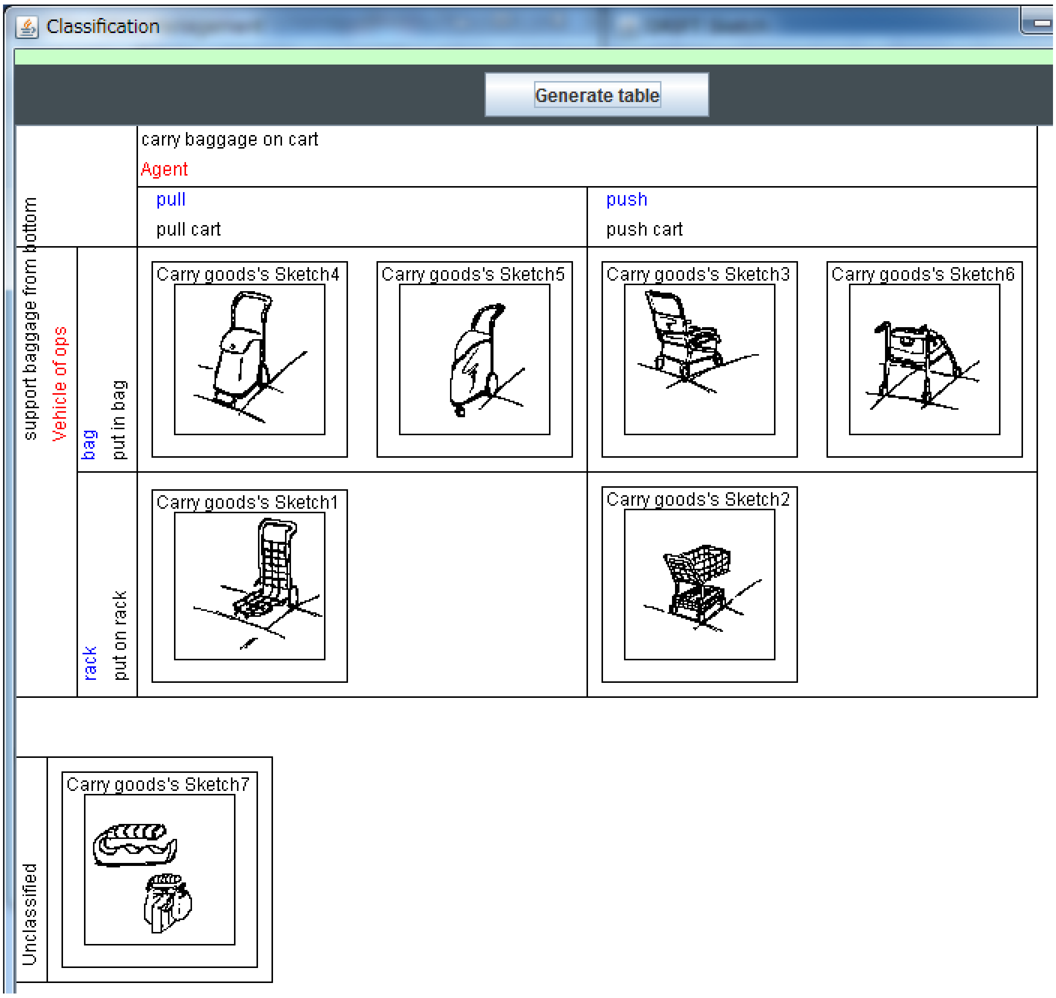


Figure 6. Initial classification table

5 DISCUSSION

A case study in Subsection 4.2 shows that a prototype system supports a methodology of three interaction steps stated in Section 3. Function classification criteria help find new function concepts that are not found intuitively such that defects of a classification are resolved. Consequently, many voids triggering new ideas can be found. A designer can generate a new idea shown in Figure 8 that cannot be generated without a support methodology. It verifies that the proposed methodology is useful for design concept generation.

Although a proposed methodology promotes systematic design concept generation, this research does not focus on how a designer creates new concepts after finding void. Some systematic approaches such as TRIZ (Altshulller, 1984) will be useful to generate new design solutions ideas. A designer should evaluate many ideas and choose valuable ones. Concept evaluation methods, such as Pugh's method (Pugh, 1991) and a selection chart (Pahl, *et al.* 2007) will support it. A methodology proposed in this paper can be incorporated with those methods. The other remaining issue is how a designer chooses axis concepts for making a classification table. It can be performed by trials and errors, but it is generally not easy to set effective axis concepts that would suggest fruitful voids when a large number of sketches are generated. One of possible approach for this issue is to define patterns of finding voids based on case analysis of cognitive aspects of design concept generation.

6 CONCLUSIONS

This research focuses on the interactive steps among concept operation and sketching activities behind design concept generation, and proposed a computational support methodology that helps a designer systematically find new concepts which cannot be noticed intuitively. This methodology consists of three steps, i.e., representing design concepts with sketching, classifying concepts with the function ontology, and finding new design concepts with the void theory that sees design concept generation as a process to resolve defects of the classification. A prototype support tool was implemented based on the proposed methodology. A case study of easy carry tool design is shown to demonstrate its validity and possibility. Finally, this paper discussed our future works. Our future works include resolving remaining issues stated in Section 5.

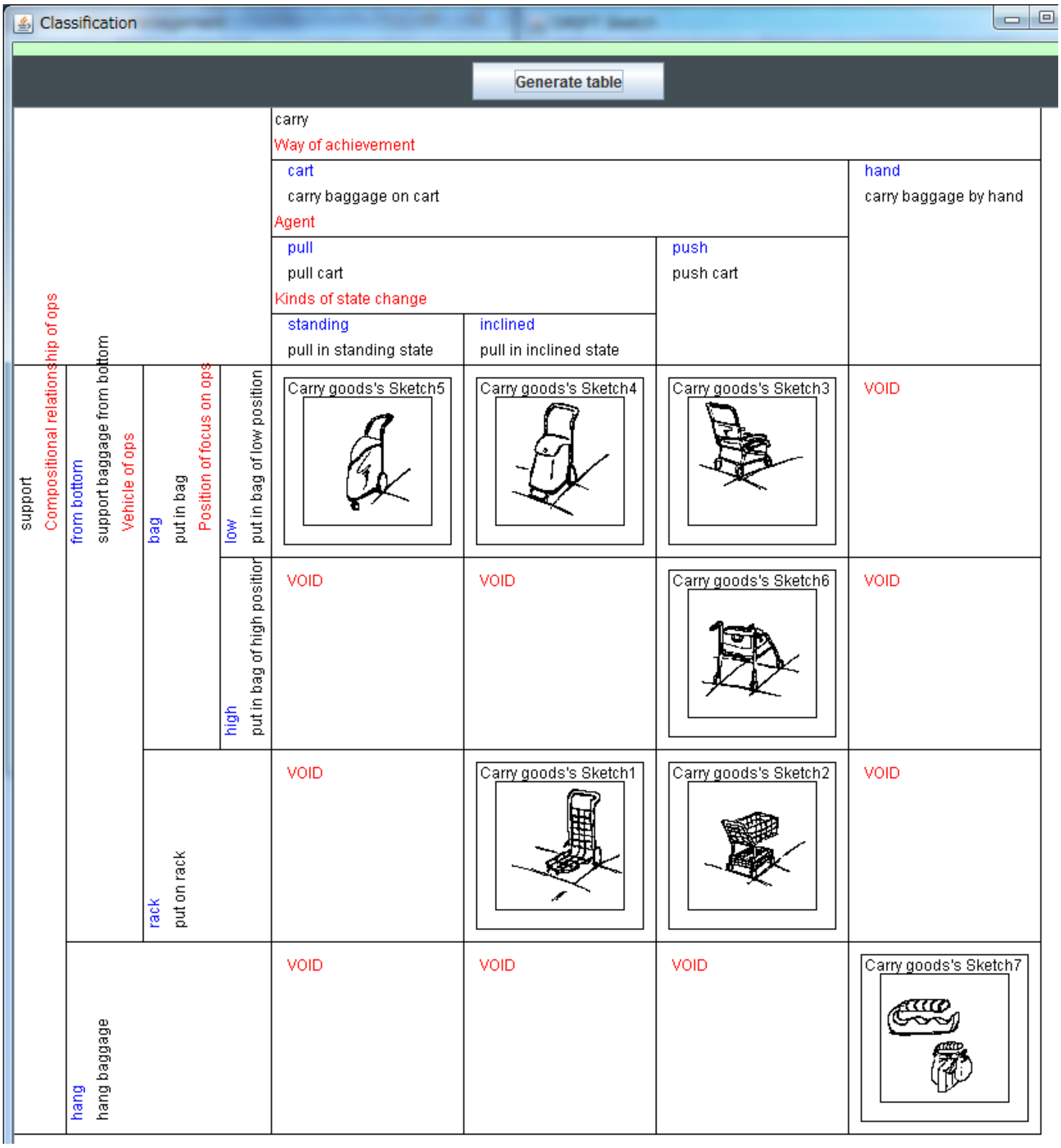


Figure 7. Revised classification table

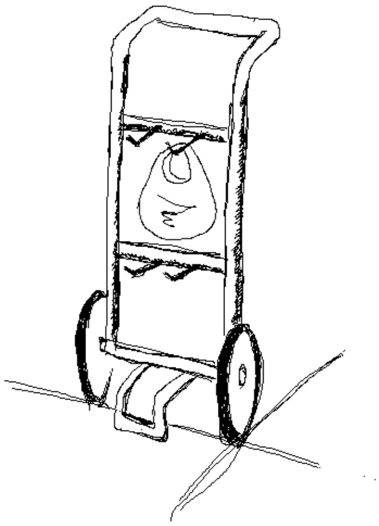


Figure 8. New idea sketch

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