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A METHOD ABOUT THE COMPONENT CONVERGENCE DESIGN FOR FUNCTIONAL ADAPTABILITY

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Abstract: Adaptable-function mechanical systems are versatile in functionalities by replacing some of their structural components, hence are compact and has wider application. Current work on supporting these products design is primarily based on a modular design approach. In this paper, we propose a novel method by exploiting a combination-based design synthesis strategy, by which the existing products can be redesigned into adaptable-function products. Firstly, the similarities of structural components delivering different functions are investigated, from which the applicable component families can be determined. After that, a method called *convergence design* is proposed to get the sharing components from the component families. Based on these results, the component associated diagram of all relevant individual products are subsequently reconfigured to generate the concept scheme of the desired adaptable-function system. At last, an innovative design of a brush with two functions is taken as a design case to illustrate the feasibility of the above concepts and methods.
Keywords: *Adaptable-function mechanical system, similarity, component family, convergence design*

1. Introduction

The mechanical products with multiple functions and compact structures would have a great market demand. Adaptable-function mechanical systems are just such products, which can deliver a variety of functions by replacing some of the components of the system (Yu & Deng, 2014), such as a combination machine tool, a multi-function screwdriver, and so on. Adaptable-function mechanical system belongs to the category of multi-function machine, but it is different from the ordinary multi-function machine that is with a fixed structure. Adjustable and/or replaceable structure is better than fixed structure because it helps to reduce the size and complexity of system structure, hence ensuring better quality and higher strength of the product in use.

The concept of adaptable-function mechanical system provides a new method for the innovative design of mechanical products. In a sense, the design process of adaptable-function mechanical system can be regarded as an evolutionary process from multiple products to an adaptable-function product; or in other words, it is the conversion process from multiple individual functions to multiple adaptable functions by some kinds of combination operation. Regarding combination-based design, there are already some research work done besides the commonly known modular design method. For example, Zou et al. (2008) proposed the concepts of combination rule and combination-based innovation method for design synthesis and for product innovation. However, there lack concrete implementation methods. Che et al. (2001, 2002) studied on the innovative design of the combination mechanism, and categorized the combination operations into several types, including serial connection, parallel connection, mixed connection, closed connection and superposition connection. Unfortunately though, their study was aimed at realizing a single function from combination, which was not consistent with the adaptable functions involved in this paper.

As can be seen, it is necessary to carry on further research and improvement on the combination-based design synthesis methods. For the adaptable-function mechanical system design, the target of design synthsis is to combine individual products into the desired system in such a way that some components of individual products shall be shared when delivering individual adaptable functions – in other words, the system should be able to deliver different adaptable functions by only replacing those un-shared components with the components that are specifically for the function to be delivered. To investigate the appropriate combination-based design synthesis method, this paper shall first analyze component similarities among multiple individual products delivering different functions, and then determine the applicable component family according to the degree of similarity. Subsequently, a so-called *convergence design* shall be proposed to be applied to the components in the applicable component families, so as to derive the sharing components, which can satisfy all or some functions of components in the component family at the same time. Based on these results, a component association diagram is reconfigured to generate the new diagram for the adaptable-function mechanical system, which is then used for the development of the desired design scheme.

2. The determination of applicable component family

2.1 The definition of component family

The structural component of an adaptable-function mechanical system can be categorized into two classes: the Basic Structure class and the Attached Structure class. The Basic Structure (BS), consisting of sharing components, is a structural unit that is needed in the implementation of multiple adaptable functions. The Attached Structure (AS) is a structural unit, which is necessary for one function but not for others. From the perspective of components, the adaptable-function design process is actually a process to achieve evolution from one adaptable function to another, which is in effect a process from some components (excluding connections, such as screws, nuts, etc., and in addition, two symmetric components can be regarded as one), called *component family*, to *sharing components* by convergence design. The whole process can be simply represented in Figure 1.

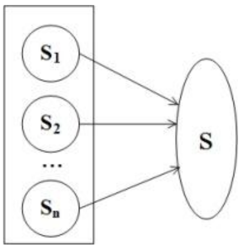

Figure 1. The design process of obtaining the sharing components

In Figure 1, S_i represents a component extracted from the i^{th} individual product, and S_1, S_2, …, S_n are extracted and together, they are considered as a component family because they are similar in some aspects. S represents the sharing component by convergence design to be discussed in the following sections. Note that for an adaptable-function system, there might exist more than one component family, hence more than one sharing component.

There are two principles in the extraction of individual components and in the formulation of component family:

(1) Exclusion principle. Two or more components from one product function are not allowed to appear in the same component family. This is because the components from a same product are not useful to get a feasible sharing component, and it would cause more complexity for the subsequent convergence design.

(2) Single principle. A component extracted for one component family will not be allowed to be

extracted for another. Convergence design is a process of redesign, thus if a component appears in two or more component families, it would means that the component will be re-designed from multiple design directions. In other words, the function information of the component will appear in more than one sharing component, which will not only cause the redundancy of design information, but will also likely cause structural conflict.

Note that not all of component families can be redesigned to sharing components through convergence design. An obvious logical thinking is that the greater the component similarity is, the easier the process of convergence design. For example, when the elements of component family are the same, i.e. $S_1=S_2=...=S_n=S_0$, the design process of sharing component will be very simple, $S=S_0$. And if they do not have the same characteristics, the design of convergence process would become quite difficult, and it is hard to get a sharing component, satisfying all the design constraints. So it is helpful to conduct the convergence design by analyzing the products similarity first to determine the so-called *applicable component family*.

2.2 Component similarity analysis

There are a lot of researches on component similarity analysis (Zhou, 1998). Wei et al. (2007) studied the similarity from the relationship of component shape topology, geometry and location, based on which they proposed a method for similarity calculation. Wang et al. (2005) analyzed the component similarity of rotational components from three layers (basic information layer, the feature information layer and the characteristic feature layer), and they presented a measurement method of similarity coefficient. Gu et al. (2006) analyzed the similarity of components by comparing the characteristics and properties of the same type of components in the mechanical repository, and provided a method of expressing similarity. To summarize, the current studies on component similarity can be categorized into three types (2004): First, the components are classified into groups according to a certain criteria, and used the same or similar method to analyze similarity of components in the same set. Second, the method of comparing similarity can be obtained by feature encoding, or by feature constraints based on the definition of manufacture features and characteristics relationship. Third, the similarity of components can be compared by studying the geometry and topology between the models, such as edges and surface information, and by building the graph isomorphism. All of these are helpful in calculating the similarity of the components, but the process is often complicated and tedious. For the adaptable-function mechanical system, components similarity analysis is mainly used to get a component family which is only used for designing the sharing component in convergence design. That means, it does not require high accuracy of the similarity. In addition, weighting factors are often necessary for the above calculations, which required experiences from the designers.

To address the above issue, we propose the following method for the determination of component similarity. To implement the evolution of multiple product functions to adaptable functions, let's start from the evolution of two product functions to one adaptable function. Assume that we need convert product A and product B to a mechanical system with adaptable function. And for A, the number of components is m, represented by a_i, i=1… m; for B, the number of components is n, represented by b_j, j=1… n. Then the similarity matrix of components can be established, as shown in table 1.

Table 1. Similarity matrix of components

	a_1	a_2	…	a_m
b_1				
b_2				
…				
b_n				

The similarity of components can be divided into five grades, represented by 0, 1, 2, 3, and 4, where 4 means the similarity is 100%, and 0 means completely different. Similarity can by specified by one designer or multiple designers.

2.3 Determination of the applicable component family

Assume $\langle a_i, b_j \rangle$ represents the value of similarity between two components a_i and b_j, (a_{pt},b_{qt}) represents the t^{th} applicable component family (which means there might be more than one applicable component family for a design), and $E(a_{pt}, b_{qt})$ is the value of components similarity in the t^{th} applicable component family, and *pt* indicates the subscript of component in A, and *qt* indicates the subscript of component in B. Based on the above rules and the understanding that the greater the component similarity is, the easier the process of convergence design will be, the equation for extraction of the applicable component families can be given as equation (1).

$$E(a_{pt}, b_{qt}) = \max\{< a_i, b_j >, i \subset T_1, j \subset T_2\} \tag{1}$$

where,

$$T_1 = \{1, 2, ..., m\} - \{p1, p2, ..., p(t-1)\} \tag{2}$$

$$T_2 = \{1, 2, ..., n\} - \{q1, q2, ..., q(t-1)\} \tag{3}$$

It is clear that the values of elements in the similarity may be same:

$$< a_r, b_s > = < a_k, b_l > \quad r, k \in T_1, \quad s, l \in T_2 \tag{4}$$

If the above value happens to be the largest, three conditions should be considered:

(i) While $r \neq s$ and $k \neq l$

(a_r, b_s) and (a_r, b_s) are the applicable component families respectively.

(ii) While $r = s$ but $k \neq l$

Then compare $\max\{< a_i, b_k >, i \in T_1 \text{ and } i \neq r\}$ and $\max\{< a_i, b_l >, i \in T_1 \text{ and } i \neq s\}$, the smaller one would be the applicable component family; If they are the same, any one can be regarded as the applicable component family.

(iii) While $r \neq s$ but $k = l$

Then compare $\max\{< a_r, b_j >, j \in T_2 \text{ and } j \neq k\}$ and $\max\{< a_s, b_j >, j \in T_2 \text{ and } j \neq l\}$, the smaller one would be the applicable component family; Any one can be taken as the applable component family when the two are the same.

The determination process of the applicable component families can be simplified by setting a similarity benchmark, and the detailed process is showed in Figure 2.

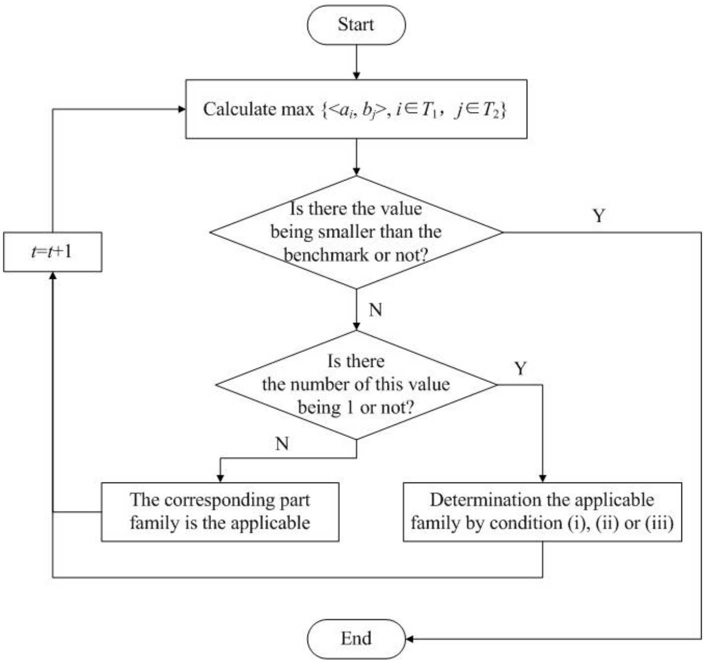

Figure 2. The determination process of the applicable component family

3. The strategy of convergence design

The purpose of convergence design is to remove the differences among components in the applicable component family, which may be caused by the different design requirements and manufacturability constraints. We propose two solution strategies for convergence design as follows.

(1) Compromise and replacement

Compromise means that some attributes of one component compromise toward attributes of the other components in the component family. *Replacement* means that some attributes of components are replaced by new attributes. This solution strategy is mainly used to address two kinds of component differences: one is due to the material or feature size difference, when their shapes are the same in the applicable component family; the other is for the situation when their shapes are different.

Let's take a group of individual products as shown in figure 3 as an example. It is clear that the lengths of the handles are different among the shovel, the axe, the saw and the knife. So are their shapes (the handle of the saw and that of the knife are both in flat shape, and the others are commonly cylindrical). Based on the above strategy, during the convergence design, a new length is used to replace their normal lengths, and the shapes can be compromised toward flat.

Figure 3. A group of products for component convergence design

(2) Disassembly and addition

Disassembly means that divide a component feature into two or more features, while *addition* means adding some new features to one or two components for making them identical, or for addressing the connection problem after disassembly. This strategy is mainly used upon the situation that the shapes of the two components are different.

We can take the conceptual design of a multi-functional screw driver as an example to explain this strategy, as is shown in Figure 4. Usually there is only one single component for a screwdriver, so is a Phillips screwdriver. Their shapes are however different. By applying the above strategy, we can divide them both into a handle and a cutter head respectively, and obviously some new features should be added for connection between the handle and the cutter head. As such, the design scheme of a multi-functional screw driver is achieved, as is shown in Figure 4.

Figure 4. A multi-functional screwdriver

4. The reconfiguration of the component associated diagram

The *component associated diagram* refers to using the undirected graph to express the component relationship for a product, shown in Figure 5. If there is direction link, e.g. the two components are geometrically in contact with each other, or one component is assembled with the other, there should be line connecting the two in the graph; if not, there is no line between them.

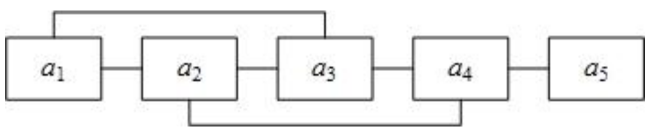

Figure 5. Component associated diagram

The generation of sharing components shall cause multiple products be linked with each other, and the component associated diagram of the adaptable-functional machine would be obtained by reconfiguration of the associated graph by taking into account such a link or links. The detailed process is shown in the following by a simply example.

Assume that the product A has three components, the product B has four components, and their component associated diagrams in shown in Figure 6 and Figure 7 respectively.

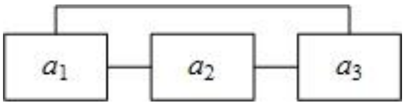

Figure 6. Component associated diagram of A

Figure 7. Component associated diagram of B

Assume that (a_1, b_1) and (a_2, b_2) are two applicable component families. Through convergence design, (a_1, b_1) is redesigned into a sharing component c_1, and (a_2, b_2) is redesigned into a sharing component c_2. Meanwhile, there is another component a_4 being generated from a_2 by using the aforementioned disassembly strategy. By reconfiguration, the component associated diagram of the adaptable-function machine is generated and based on this, the BS and AS can be obtained. The results are illustrated in Figure 8.

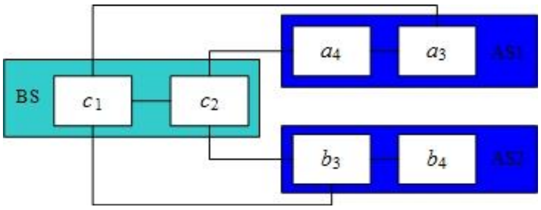

Figure 8. The component associated diagram designed for an examplar design case

5. Cased study

In this section, we apply the above methods to design an adaptable-function product, which is a new brush with two functions, shoe brush and common brush, creatively.

There are presently two kinds of brushes used in our daily life, as shown in Figure 9 and Figure 10 respectively. Usually the length of the shoe brush is larger than that of the other, while the width of the shoe brush is smaller, because of the different application environment. It is easy to understand that a new brush with two functions would be good for reducing material usage and for being more convenient in usage. To this end, we can design such a product in the following steps.

Figure 9. A shoe brush

Figure 10. A common brush

1. Determine the applicable component families

It is evident that a shoe brush can be divided into two components, the brush (a_1) and the brush handle (a_2), while the common brush is consisting of the brush (b_1) and the brush handle (b_2). Because the structures are very simple, the applicable component family can be determined directly into (a_1, b_1) and (a_2, b_2).

2. Apply convergence design to the applicable component families

Firstly, for a_1 and b_1, there are differences in both the quantity of the brush hairs and materials used. For the materials issue, it does not matter much to the function by using either of the existing two materials, so the compromise and replacement strategy can be used to address the difference. For the quantity issue, the disassembly and addition strategy is just the right choice. We can split the brush component of the common brush into two components (b_3 and b_4). With these operations, b_3 and a_1 would become identical, namely a sharing component indicated as c_1 can be derived, and b_4 is a new component from b_1.

For a_2 and b_2, there are differences in shape, size and material. The compromise and replacement strategy can be applied to address the differences in shape and material. And for the size issue, the disassembly and addition strategy is useful. Divide the handle of the shoe brush into two components (a_3 and a_4) and the handle of the common brush into three components (b_5, b_6 and b_7), then b_6 and a_4 are the same, namely a sharing component indicated as c_2 is derived, while b_5 and a_3 are same, namely a sharing component indicated as c_3 is derived. Subsequently, by reconfiguration, the component associated diagram of the new brush can be obtained, as is shown in Figure 11.

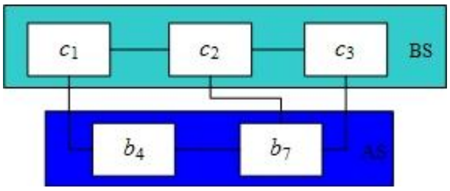

Figure 11. The component associated diagram of the designed new brush

From the diagram shown in Figure 11, a more detailed design scheme can be further developed. For example, there is no brush in the handle of the shoe brush, which means its thickness should be smaller than that of the handle of the common brush. The detailed scheme of the new brush is shown in Figures 12, 13 and 14.

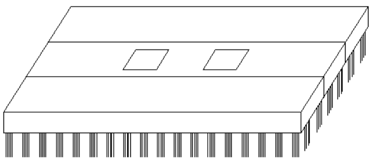

Figure 12. The new brush as a whole

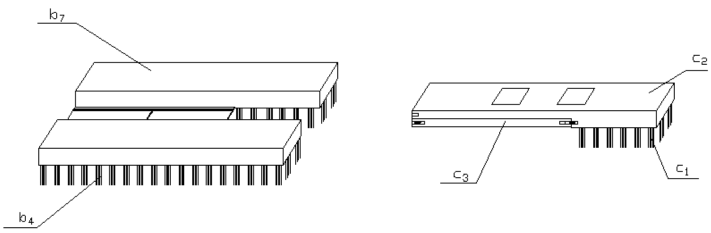

Figure 13. The exploded view of the new brush with the components labelled

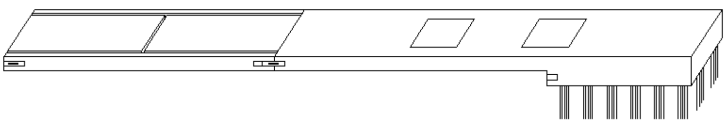

Figure 14. The shoe brush ready for use

6. Conclusions

This above sections proposed a few strategies and methods for redesigning multiple individual products into an adaptable-function product, which was verified by the design process of a new brush with two functions. It is noted that further work is necessary, for example, the proposed component associated diagram is a bit simplified, which does not express the difference on the constraint relationship between components, thus more professional knowledge and designer's own experience are necessary during the subsequent reconfiguration process. Future work should also focus on computer implementation technology, so as to implement and further improve the above ideas.

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