Functional Surface Reasoning Strategies in Product Growth Design

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Abstract. Based on the systematic analysis on the principles of conceptual design, the key technologies of functional surface reasoning in product growth design are discussed. Firstly, the basic concept of product growth design, functional surface as well as Generalized Positioning Principle (GPP) are given. Secondly, the functional design principles based on function surface reasoning are proposed, in which three reasoning rules on relationships among functional surfaces are developed. Thirdly, by transferring the product motion into its relative mechanical transmission, functional-surfaces relationship reasoning strategies are put forward based on kinematic joints. Those methods offer good analyses and descriptions of the orderly evolution process of the product function and structure, in a proper sequence from functional requirements to functional models, then to product motion transmission chain, finally to functional surface pairs constructing the product motion transmission chain. Finally, an example is given to verify the effectiveness of the proposed method.

1. Introduction

Being a very important design phase, conceptual design has significant influence on product performance, functionality, reliability and customer satisfaction. In this phase, the designer must deliver an initial design that defines “working principles” or even give practical solutions corresponding to these “essential” principles. Among the variety of design methods, biological design throws new light on the initial concept design domain[1].

With the stepping forward of design process, the information will be enriched, extended and explored. The mode in which the original and initial design information is expanded and transferred is similar to that of the inheritance and evolution of life growth[2]. Great attention has been paid to exploring the mechanism of applying life phenomenon into the product design area[3], among which reasoning methods and algorithms are widely used to solve growth design problems. In literature[4], the graph-based reasoning operations for the integration and comparison of several conceptual graph rules corresponding to different viewpoint of experts were proposed. In Peng’ s paper[5], an approach combining the RBR with fuzzy comprehensive judgment method was proposed for locating schemes and locating features. To serve the computer-aided conceptual design on the basis of the function-behavior-structure procedure, the computerized rules and steps for the behavior set grouping were studied in literature[6]. By integrating case-based reasoning and the TRIZ method, a novel model to accelerate the preliminary eco-innovation product design was proposed by Yang and Cheng[7].

Nowadays, the reasoning technologies for conceptual design have been developed. However, several aspects that should be further discussed and studied. Such as, how to apply the reasoning technologies to practical design processes more efficiently and how to obtain the conceptual scheme solutions through the integration of various reasoning technologies. The purpose of this paper is to put
forward some effective solutions on functional surface reasoning. The automatic and concurrent
design of product conceptual structure can then be realized by using those solutions.

2. Incremental product growth design

Starting from the functional requirement, the incremental growth design process is to establish the
complicated mapping from the functional requirement domain to the physical structure domain of a
product. Here, the incremental growth design process of a roller fixture is shown in figure 1. Figure
1(a) shows the first step of the process, during which the visual shape of the product prototype is
generated according to the design requirement. Prototype is physically represented as the composition
of functional surfaces, and it contains information on product structural and functional features such as
structural characteristics, assembly ability and mechanical features. Similar to the “cell division and
growing” process of biology, figure 1(b) to figure 1(g) are the mapping process from the functional
domain to conceptual product, during which functional surfaces are decomposed into several
functional envelop surfaces. Figure 1(g) shows the conceptual structure of the roller fixture, which
includes a string of functional cells constituted by functional components and the correlation
information among functional surfaces. Then from those functional envelop surfaces, the product
structure are “grown up”, as shown in figure 1(h).

Figure 1. An example of product growth design.

Product growth design focuses on the evolution of products from scratch, based on which the
product can be able to grow up step by step from functional requirements to the final geometrical
product structure automatically. So, the principles of the product growth design are mainly embodied
in the following two aspects:

(1) The basic functional and structural carriers of the growth design process are the functional
surfaces.

Functional surfaces are the interfaces between two components that contact with each other, which
make them be good carriers of function structure mapping, while they are conceptually the function
information carriers that represent designer’s design intentions, as shown in table 1.

| Functional surface | Figure | Function | Functional surface | Figure | Function |
|--------------------|--------|----------|--------------------|--------|----------|
| Small face         | ![Small face](image) | $T_x$ | Conical surface    | ![Conical surface](image) | $T_x$, $T_z$, $T_y$, $R_y$, $R_z$ |
| Face               | ![Face](image) | $T_x$, $R_y$ | Spherical          | ![Spherical](image) | $T_x$, $T_z$, $T_y$ |
| Long face          | ![Long face](image) | $T_x$, $R_y$ | | | |
(2) The traditional six-point location theory is expanded to Generalized Positioning Principle (GPP). Traditional six-point location principle can only be used for the positioning design of product in motionless status. During the product design process, the pattern of a kinematic pair between two components determines the assemble constraints between them and the function that can be realized. In order to realize the dynamic and automatic design of product driving train and transmission chain, the traditional three-dimensional space is expanded to generalized four-dimensional space. That is:

Any component in a product is a closed space region enclosed by half-direction surfaces. At every instant, sufficient and appropriate surfaces should be involved to contact with each other, whether they are moving or not. Under the generalized force, 12 spatial half-DOFs of the part are all limited, including 6 translation half-DOFs along the positive and negative directions of the coordinate axis $Z, Z, Y, Y, X, X$, as well as the 6 rotation half-DOFs around the coordinate axis $Z, Z, X, X, Y, Y$, which are displayed in figure 2.

![Figure 2](image1)

**Figure 2.** The origin of Generalized Positioning Principle (GPP).

Figure 3 presents an example of Generalized Positioning Principle. To realize the generalized position of a cylinder, functional surfaces must be used to limit the DOF on $T_x, T_y, R_x, R_z$, as shown in table 1. Therefore, two small faces on the top are applied to limit the 4 rotation half-DOFs around the coordinate axis $X, X, Z, Z$, that is $R_x, R_z$. Other two small faces on the end sides of the cylinder are used to realize the limiting of 4 translation half-DOFs along the coordinate axis $Y, Y, Z, Z$, that is $T_x, T_y$. The functional surfaces group can finally evolve into parts as shown on the right side of figure 3.

![Figure 3](image2)

**Figure 3.** Example of Generalized Positioning Principle.

### 3. Functional surface reasoning

During growth design process, product structure can be generated during the decomposition and reconstruction of the functional surfaces step by step. Under the driving of technical specifications, the key structural feature representing the topological relationship between the functional surfaces can be produced. And by using the target values of technical features as the constraints, structural parameters, such as dimension and tolerance parameters can be generated. So, the following three reasoning rules on the relationships among functional surfaces composing the product structure, are exist:

1. Only functional surfaces with same functional semantics and fixed connecting relationship can form a possible component;
(2) Structural characters and structural parameters related with functional surfaces in the same function parts can be developed into the shape feature constraints and the internal shape dimensions of a component;

(3) The assemble constraints and location dimensions among components are generated from structural characteristics and structural parameters related with functional surfaces in different parts.

Multi-stage transmission mechanisms constitute the transmission chain of the whole system. Each level of the transmission chain is achieved by kinematic joints which are formed by functional surfaces belonging to different parts. Normally, functional surfaces interact with each other when they are contacted. That means, one surface limits the spatial DOF of the other. Based on these location limits among functional surfaces on different components, the kinematic function of a product can be achieved, as presented in figure 4.

![Figure 4. Transmission function carried out by different carriers.](image)

The types of the two contacted surfaces and contacted patterns between them have an important influence on the types and numbers of the DOF being limited. The motion conversion among functional surfaces of transmission parts can be expressed as the followings:

\[ T \leftarrow T', T' \leftarrow R, R' \leftarrow R, R \leftarrow T' \]

In which, “R” stands for basic rotation DOF, including \( R_0, R_1, R_2, R_3, R_4 \), which means arbitrary rotation, rotation around any axis along the constraint direction, rotation around a constraint axis, rotation around a constraint point, no rotation, respectively. And “T” mentioned above means basic translation DOF, including \( T_0, T_1, T_2, T_3, T_4 \), which means arbitrary translation, translation along a constraint plane, translation along a constraint axis, translation along a constraint direction, no translation, respectively.

According to the relationship between the functional surface pairs and the DOF, proper functional surface pairs can be chosen to realize the above mentioned four kinds of motion conversion, as displayed in table 2.

| Motion | Surface pairs | DOF | Surfaces’ relationship |
|--------|---------------|-----|------------------------|
| \( T \rightarrow T \) | Plane pair | \( R_1 \rightarrow T_1 \) | Two planes are tangent totally |
| \( T \rightarrow T \) | Cylinder pair | \( R_2 \rightarrow T_2 \) | Two cylinders are tangent totally |
| \( T \rightarrow T \) | Cone pair | \( R_2 \rightarrow T_2 \cup T_3 \) | Two cones are tangent totally |
| \( T \rightarrow R \) | Cylindrical friction pair | \( R_2 \rightarrow T_4 \) | Translating in the same direction of the rotation speed |
| \( T \rightarrow R \) | Cylindrical thread pair | \( R_2 \rightarrow T_4 \) | Translating in the direction intersecting with the direction of the rotation speed |
| \( R \rightarrow R \) | Conical thread pair | \( R_2 \rightarrow T_2 \) | The two rotation axes are parallel |
| \( R \rightarrow R \) | Cylindrical gear pair | \( R_2 \rightarrow T_2 \) | The two rotation axes are in different planes |
| \( R \rightarrow R \) | Helical gear pair | \( R_2 \rightarrow T_2 \) | The two rotation axes intersect with each other |
| \( R \rightarrow R \) | Worm gear pair | \( R_2 \rightarrow T_2 \) | The two rotation axes intersect with each other |
| \( R \rightarrow R \) | Conical gear pair | \( R_2 \rightarrow T_2 \) | The two rotation axes intersect with each other |
4. Design example

In this part, the conceptual design of the conveyer of a spring sorting machine is used as an instance to explain the reasoning process mentioned above.

Firstly, the product prototype from the workpiece is extracted. According to the generalized localization principle and the functional information transmitted by the spring, generalized positioning mode can be extracted from the existing artifact spring entity model. As shown in figure 5, considering the transportation of the springs along the conveyer, 8 DOFs of the artifacts should be limited. They are $X, X, Z, Z, X, X, Z, Z$.

![Figure 5. The generalized positioning mode of the artifacts.](image)

Secondly, the corresponding positioning surface from the artifacts model is selected. This surface can be evolved into two groups of surface pairs, one of which represents the artifact itself, and the other is the prototype of the sorting machine, as shown in figure 6(a). The prototypes of the conveyer and the corresponding positioning pieces are the long cylindrical surfaces on the right side of the figure 6(b), which can limit 8 DOFs, including $X, X, Z, Z, X, X, Z, Z$. The two toroidal surfaces decomposed from the artifact’s two end faces are the prototype of the detection device. They can limit 2 DOFs, namely $Y, Y$, as shown in figure 6(c). As a result, the artifact’s generalized positioning can be realized.

![Figure 6. Generation of the original conceptual model of the spring sorting machine.](image)

Thirdly, analyzing the motion requirements of the artifact and the motion mode of the power source, then, the transmission path can be generated. All transmission pairs which can realize the motion transformation can be obtained according to table 1. For example, the transmission pair to realize the motion transformation $R_x \rightarrow R_y \rightarrow R_z$ can be described as,

worm and gear pairs (or conical gear pairs) $\rightarrow$ cylinder friction pairs (or cylinder thread pairs).

According to table 2, 40 kinds of transmission chains can be obtained. Obviously, compared with the units shown in figure 7, these transformation chains mainly show spatial location adjustments, substitutions of previous and next units, etc.

After the comparison of those motion transformation chains, the best solution can be achieved, that is $R_x \rightarrow R_y \rightarrow R_z$, as shown in figure 7(a), it can be selected as the final transformation type.

![Figure 7. The optional mode of the transmission system.](image)
The design result of the product conceptual structure is presented in figure 8.

Then, the decomposition process of the transmission chain based on the dynamic assembly decomposition can be described as:

square groove→conveyer→roller→worm and gear joints →electromotor

Based on the process abovementioned, the conceptual structure of spring sorting machine can be gained, as presented in figure 9.

5. Conclusions
In the growth design process, in order to realize the effective mapping from the functional demanding, to basic physical structure, the functional surface reasoning strategies are studied in this paper. By decomposing the product motion behaviors into relative motion and mechanical transmission, the kinematic joints based functional surfaces reasoning strategies are given. This method offers an orderly product function and structure evolution process from functional requirements, to function model, then to product motion transmission chain, finally to functional surface pairs constructing the product motion transmission chain. The research findings will be useful to the transformation of qualitative design to the quantitative design in biological evolution design area, and beneficial to develop a new method and provide technology support for the realization of the product self-organizing intelligent design.

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